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Tactile Displays for Pedestrian Navigation

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Abstract

Existing pedestrian navigation systems are mainly visual-based, sometimes with an addition of audio guidance. However, previous research has reported that visual-based navigation systems require a high level of cognitive efforts, contributing to errors and delays. Furthermore, in many situations a person's visual and auditory channels may be compromised due to environmental factors or may be occupied by other important tasks.

Some research has suggested that the tactile sense can effectively be used for interfaces to support navigation tasks. However, many fundamental design and usability issues with pedestrian tactile navigation displays are yet to be investigated.

This dissertation investigates human-computer interaction aspects associated with the design of tactile pedestrian navigation systems. More specifically, it addresses the following questions: What may be appropriate forms of wearable devices? What types of spatial information should such systems provide to pedestrians? How do people use spatial information for different navigation purposes? How can we effectively represent such information via tactile stimuli? And how do tactile navigation systems perform?

A series of empirical studies was carried out to (1) investigate the effects of tactile signal properties and manipulation on the human perception of spatial data, (2) find out the effective form of wearable displays for navigation tasks, and (3) explore a number of potential tactile representation techniques for spatial data, specifically representing directions and landmarks. Questionnaires and interviews were used to gather information on the use of landmarks amongst people navigating urban environments for different purposes. Analysis of the results of these studies provided implications for the design of tactile pedestrian navigation systems, which we incorporated in a prototype. Finally, field trials were carried out to evaluate the design and address usability issues and performance-related benefits and challenges.

The thesis develops an understanding of how to represent spatial information via the tactile channel and provides suggestions for the design and implementation of tactile pedestrian navigation systems. In addition, the thesis classifies the use of various types of landmarks for different navigation purposes. These contributions are developed throughout the thesis building upon an integrated series of empirical studies.

Preface

All work presented in this thesis is original work unless indicate otherwise. Parts of this thesis have been published as follows:

Related to Chapter 4:

Srikulwong, M. and O'Neill, E. (2011a). A Comparative Study of Tactile Representation Techniques for Landmarks on a Wearable Device. In Proceedings of the 29th *International Conference on Human Factors in Computing Systems (CHI 2011)*. Vancouver, Canada. ACM Press, pp.2029-2038.

Srikulwong, M and O'Neill, E. (2011b). Wearable Tactile Display of Landmarks and Direction for Pedestrian Navigation: a User Survey and Evaluation. *International Journal of Mobile Human Computer Interaction*, 3(3), pp.31-49.

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Related to Chapter 3:

Srikulwong, M and O'Neill, E. (2010c). A Comparison of Two Wearable Tactile Interfaces with a Complementary Display in Two Orientations. In Proceedings of the 5th *International Workshop on Haptic and Audio Interaction Design (HAID 2010)*. LNCS 6306. Copenhagen, Denmark. Berlin: Springer, pp.139-148.

Srikulwong, M. and O'Neill, E. (2010a). A Direct Experimental Comparison of Back Array and Waist-Belt Tactile Interfaces for Indicating Direction. In Proceedings of *Workshop on Multimodal Location Based Techniques for Extreme Navigation* at Pervasive 2010. Helsinki, Finland. HaptiMap Project, pp.5-8.

This thesis has not been submitted for a higher degree to any other University or institution.

Mayuree Srikulwong

Though pleased to see the dolphins play, I mind my compass and my way.

(Matthew Green, 1737)

Chapter 1 Introduction

The motivation of this thesis stems from the fact that humans navigate on a daily basis. The history of navigation dates back to the days when humans lived in rural areas. In 1800, only 3% of the world's population lived in cities (The Economist, 2007). We migrated and discovered new lands by navigating the oceans. Ancient travellers like the Greeks and Phoenicians relied on all five senses, but mainly the *visual* one, to gain an awareness of the environment and develop navigation skills helped by natural phenomena such as the Sun, the Moon, stars and wind. A visual approach to navigation using a paper-based map and a magnetic compass requires various sets of skills and cognitive effort. Regularly, we suffered from environmental fluctuation and impoverishment (e.g. atmospheric conditions, fog, cloud, and navigation in the dark or in forests).

Since 1950, the shift in rural to urban lives has been exponential. As of 2008, more than 50% of the world's population live in the cities (Zuckerman, 2011). Specifically, over 75% of the population in highly developed countries live in the cities whereas the figure for the least developed country (classified by the UN) stands at 29% (The World Bank, 2011). Cities promise opportunities and options for living (Zuckerman, 2011) but entail navigation complexity. Even though in modern days we have invented navigation techniques and visual technologies to help us with navigation, we still suffer from the same environmental factors. Furthermore, new technologies, known as Global Positioning System (GPS) or Satellite Navigation System (SatNav)[1], impose new problems such as mental disorientation (Seager et al., 2007) and disengagement from the environments (Leshed et al., 2008).

City lives and urban environments do not always allow us to navigate easily. We live in an era when we naturally multitask while moving (Tamminen et al., 2004). Difficulties in navigation are more emphasised when we travel to new places. There are elements of differences in architecture, layout, environmental features and people in those spaces with

[1] GPS or SatNav refer to a system of satellites for navigation that provide precise geo-spatial positioning (longitude, latitude, and altitude) and time with global coverage.

which we have to interact throughout the course of navigation. Our visual channel is pushed to excess; our cognition is overloaded by information from the world and the tools.

Despite a high cognitive demand required by visual navigation displays, SatNavs' perceived usefulness has given rise to their popularity. Sales volumes of both SatNavs and smart phones reached close to 29 million units worldwide in 2007, and are projected to keep growing to hit 48 million units by 2015 (Chandrasekar, 2008).

For some people, using maps is difficult because it is hard to identify and locate streets, some may be printed in different languages and require the ability to interpret graphical representation in the map (Millonig & Schechtner, 2006). SatNavs can be difficult to look at given a small screen size (Tsukada & Yasumura, 2004). The situation could worsen with fluctuation in the environments, e.g. too much natural light and bad weather. Despite the flaws, visual displays dominate the market for assistive navigation tools.

In the urban context where users are required to use their visual and auditory channels to interact intensively with the world around them, more use might usefully be made of alternative or complementary sensory channels such as touch. Indeed, touch has been shown to be suitable for ubiquitous environments and to work more effectively than the visual channel under workload situations as well as in extreme conditions such as at night time (Wickens, 1980; Tan et al., 2003; Ternes & MacLean, 2008; Holland et al., 2002; Elliott et al., 2010). It is reported to help increase performance and reduce workload and task failure (Elliott et al., 2010; Weinstein, 1980; Nordwall, 2000; U.S. Air Force, 2001; U.S Army Aeromedical Research Laboratory, 2004). This thesis focuses on the use of tactile communication to support pedestrian navigation.

Research into pedestrian navigation systems is still in its early stage. This thesis examines wayfinding models of navigation as well as investigating relevant issues in order to propose innovative interactive system that allows pedestrians to navigate efficiently and effectively in urban environments aided by the tactile sense.

This thesis builds upon insights from various fields relevant to the design, development and evaluation of tactile displays for pedestrian navigation. It identifies problems with visual navigation and presents requirements for the design and development of a tactile-based pedestrian navigation system, based upon empirical findings and a rich set of guidelines for tactile interaction. These requirements draw on a series of studies in which we investigated the design, usability and user experience of prototype systems. An indepth evaluation of our prototypes allows us to develop an understanding of design for tactile-based navigation.

This chapter presents the background to this research, describing land navigation, identifying problems with visual displays and proposing research topics in tactile displays for pedestrian navigation. Research challenges and the research questions (RQs) tackled by the thesis are briefly addressed. The contribution of the thesis is briefly outlined. Finally, we introduce the remaining chapters.

1.1 Background

The thesis centres on a form of land navigation[2] called *pedestrian navigation* (i.e. navigation on foot) in urban canyons. The model of navigation for pedestrians is different from that for vehicles (Gaisbauer & Frank, 2008). Pedestrian navigation is not as constrained as vehicular navigation and more flexible. Specifically, pedestrians are not restricted by speed of vehicles and the road network (e.g. turn restriction and lane direction). As a result, it is possible that there could be many choices and shortcuts that are available to pedestrians for a particular journey. In addition, there are open-ground walking areas such as parks that pedestrians can walk freely.

1.1.1 Human navigation and pedestrian navigation

In Latin, *navigation* refers to ships. The modern day term indicates the process or activity of accurately ascertaining one’s position, planning routes, and execution of movements to follow planned routes from one place to another (i.e. destination).

Unlike migratory animals, e.g. birds and turtles, humans are not equipped with a built-in navigation system. However, for many thousands of years, we have been able to find our way over great distances and open seas with the application of intelligence and techniques including dead reckoning, maps, nautical charts, quadrant, sextant and chronometer[3].

When the Chinese created a magnetic compass, travellers were able to orient themselves and travel on a course without reference to landmarks. Nevertheless, orienteering with a

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[2] Land navigation concerns navigation on land, including navigation on foot (pedestrian) and vehicle navigation (RIN, 2011).

[3] See Glossary.

magnetic compass and map requires another set of skills in order to embark on successful route finding.

During the course of a journey, one would have to constantly match one's perception of the environment with particular features and positions on the map. Specifically, *visual navigation* requires three sets of skills: preparatory, wayfinding and locomotion. Preparatory involves route planning; wayfinding refers to the requirement to know where to go and how to get there; and locomotion is the actual movement in the intended direction as well as avoiding obstacles along the route. Travellers continuously apply these skills (i.e. perception, cognition and motor behavior) to navigate effectively.

For the preparatory part, one would require skills in map reading, i.e. understanding components of maps, which typically include the concepts of direction, scale, distance, signs, marginal information, and grid references.

For the wayfinding skills, one would have to (1) constantly locate one's position, (2) constantly check if one is on the right route or planned path, and (3) orient the map by identifying specific features (e.g. landmarks) and either locating such a map's feature to the actual feature or vice versa (Keay, 1989). In addition, one would need to be able to estimate distance.

For the locomotion skills, one would have to try to move successfully in the intended direction without injuring oneself or moving into obstacles (Montello & Sas, 2006). This requires coordination of one's sensory and motor systems to the environments. One needs to be able to identify obstacles, barriers, surfaces and other relevant features in the environment and direct one's movement toward the intended destination (Keay, 1989).

One might think that with current positioning technologies (such as GPS), one could easily determine her position with sufficient, accurate, precise, and up-to-date information provided by such systems. Such systems' perceived usefulness is reflected in the growth of satellite-based pedestrian navigation systems in mobile devices in recent years (see Chandreskar, 2008).

Despite innovations in positioning technology, problems with visual navigation are reported to have remained the same. From a human factors' perspective, one would still be required to possess a high level of skills and expected to expend a high level of cognitive effort (e.g. to map oneself with the display and the more complex world). Furthermore, there are new problems introduced by the forms of this new technology, e.g. accessibility issues caused by small screen size and bright light.

It has also been reported that a range of human factors issues, e.g. humans susceptibility to cognitive overload, form and modality of information and distractions in the environment, contribute to the failure of wayfinding with visual technologies (Montello & Sas, 2006). Investigating and understanding these issues could lead to improvements in application design and the use of alternative sensory channels that could help to minimise cognitive effort and increase the accuracy, efficiency, ease and safety of navigation.

1.1.2 Mobile visual navigation systems: advantages and disadvantages

According to market predictions, visual navigation on mobile devices is becoming dominant and the number of users is likely to increase exponentially in the next couple of years.

Millions of users benefit from such systems to aid their wayfinding tasks. At the same time, they suffer because of poor interface design, overloading content, and high cognitive demand (Huang et al., 2012). During any course of navigation it is likely that there will be some degree of mismatch of a user's perception and motor behavior among three frames of reference: the display of the system, the world and herself.

In the next part we discuss the advantages and disadvantages of visual-based mobile navigation systems.

Advantages of visual navigation systems

Their benefits include: (1) performance over traditional maps and (2) perceived usefulness.

Performance over traditional maps

Researchers report that GPS offers advantages over traditional maps used in vehicular navigation (Burnett & Lee, 2005), and the compass used in military operations (Young et al., 2008). Experimental results showed that GPS users spent less time looking at the map and less time making navigational decisions.

Perceived usefulness

According to researchers (Dillon & Morris, 1996; Varden & Haber, 2009; Hurst, 2010), GPS were perceived as useful because they were considered simple, portable, up-to-date, accurate and scalable. Users trusted the system's instructions and felt no risk; even distractions and errors were tolerable.

Disadvantages of visual navigation systems

Although visual navigation has proved to be useful for route guidance and human wayfinding, there are a number of practical and psychological issues. When we navigate, features in the physical environment remain fixed and we move across environments that may present other influential factors. The fact that we move changes our spatial relationship with our environment and gives rise to the problem of identifying spatial orientation and other problems. Known problems with SatNavs include: (1) poor positioning accuracy and poor map data, (2) poor interaction design, (3) transformation amongst frames of references (4) high level of mental orientation, (5) struggle in reduced visibility and audibility environments, and (6) loss of attention and situation awareness.

Poor positioning accuracy and poor map data

Researchers (e.g. Raper et al., 2007; RIN, 2011) in the field of positioning determination technology (PDT) acknowledge that current positioning techniques and map data are not completely reliable especially when navigating in urbanised areas. Urban users experience low availability of satellite signals because the height of buildings contributes to the blockage of satellite visibility. Patel et al. (2006) pinpointed that coarse positioning coupled with poor map and poorly designed instructions lead users astray, resulting in high cognitive load.

Poor interaction design

Current SatNavs' instruction design typically provide a moving map display and turn-by-turn directions based on distances to turn rather than landmarks (May et al., 2003; Sefelin et al., 2005), despite landmarks being described as the most important spatial information for pedestrians (Pielot & Boll, 2010). This suggestion is supported by May & Ross's (2006) study reporting that both old and young GPS users performed better with landmark-based than distance-based directions. Distance information provided in the system is difficult to interpret because it is not directly perceived from the environment (Burnett, 1998). Users are required to possess a skill that allows them to understand and estimate distance metrics. Generally, human judgment on absolute distance is far from being accurate.

Despite these drawbacks, the SatNav market is continuously growing. This growth initially responded to the desire for in-vehicular navigation systems. Unfortunately, when the system is being used for pedestrians, it lacks substantial consideration that land navigation relies on humans' inherent navigation skills. While the system tries to calculate the shortest route based on the map database, the user may work out the best path given the target landmark's visibility. The main logic of most GPS assumes that users want to be guided to the most effective (shortest or fastest) route (based on road networks) for the destination. This does not always fit with some navigation purposes. For example, a tourist might prefer to explore a new area by walking long distances; the process in this case involves planning routes, passing places of interest in the cityscape, and spending considerable amounts of time at each place.

A study by Ishikawa et al. (2008) backs this shortcoming. They compared the effectiveness of GPS-based navigation with a paper map in walking scenarios. Results showed that GPS users took longer distances, navigated slower, stopped more often and made more errors than map users. At the end of the journey, GPS users drew a poorer topological map of the navigated area. This phenomenon can be explained. Burnett & Lee (2005) found that GPS users paid less attention to the environment than map users. In conclusion, the use of GPS helps with building route knowledge but not survey knowledge (Krüger et al., 2004; Burnett & Lee, 2005; Young et al., 2008) and disengages users from the environments because their attention is preoccupied by the system's instructions (Leshed et al., 2008).

Another major design issue is the screen size of GPS. Currently, multiple types of information being displayed on a very small screen are very difficult to read. This visually cluttered screen is reported to violate cognitive ergonomics and slow down information processing (Kleppel et al., 2009). Users from Hurst's (2010) survey confirmed that they found a small screen size lowers the system's usability.

In addition to all the above issues, a recent survey by a leading UK insurance firm (Swinton, 2011) claimed that 63% of UK drivers, who own a GPS, keep paper maps in their vehicles because they consider their GPS to be untrustworthy. Satnavs are also listed as a major source of in-car bickering.

Transformation amongst frames of reference

Human can perceive the visual world and judge directions, orientation, and movements of visual objects given that we have learnt to judge images/objects with the coordinate systems: egocentric and exocentric *frames of reference* (Howard, 1993). The egocentric frame is defined with respect to some part of the observer, being the nodal point of the eye, the retina, the head or the body. An exocentric frame of reference is external to the observer such as geographical coordinates and the direction of gravity.

Wicken et al. (2005) defined that frames of reference can be: (1) a *world* frame in which the surrounding space is represented (e.g. North, East, West, South), (2) an *ego* frame representing the momentary location and orientation of the user's trunk (e.g. left or right in reference to the body trunk), (3) a *head* frame representing the orientation of the head (i.e. head orientation which might be different from ego-trunk), (4) a *display* frame where the orientation of the display and information movement is shown, and (5) a *control* frame, which is the orientation and movement of the control unit of the display (e.g. buttons on a display device).

The navigation function through the visual channel involves transformation among at least three frames of reference: world, ego and display frames, in both two-dimensional (2D) and three-dimensional (3D) spaces. Most of the visual navigation displays provide two inputs: forward field of view (FFOV) and guidance information (e.g. maps), specifically with three kinds of information: (1) navigational choices, (2) spatial direction judgments of the object, and (3) navigational checking (am I on the right path?). Problems occur when there is a mismatch among the 3D world FFOV view of self and the 2D map view. The need for transformations amongst frames of references happens in real time and varies in difficulty (Corballis, 1982). This is believed to decrease user performance (Montello & Sas, 2006). These transformations are sources of time delay, errors and mental workload (Wickens, 1999). Other minor issues include the differences in resolution and shape of objects that lead to ambiguity problems.

High level of mental orientation

In navigation, orientation refers to the determination of one's position relative to the destination and specific features, e.g. places and objects, on routes. Many researchers (e.g. Seager & Stanton Fraser, 2007, Smets et al., 2008 and Namiki et al., 2010) pinpoint orientation and performance problems in using visual maps to assist egocentric tasks[3] like navigation. Disorientation occurs when travellers are not confident or fail to locate where they are or which way they need to go in relation to the information provided by the visual displays. During the course of navigation, there would be circumstances, e.g. a case of

[3] An egocentric task is when one has to judge the position, orientation or motion of an object with respect to an egocentric frame of reference.

slow system update, when the top of the map displayed is not aligned with the forward direction of the user's movement (i.e. different frames of reference do not match).

In these cases, the human operator has to perform extensive mental rotations, e.g. between the ego-trunk and the map, while carrying out their tasks. A user may physically or mentally reorient the map or herself by matching features on the map with those in the immediate surroundings so that she will always get a head-up map. Head-up maps are found to hold a positive effect on navigation performance (Aretz, 1991; Smets et al., 2008; Seager & Stanton Fraser, 2007; Namiki et al., 2010). Sometimes disorientation may result in life threatening or serious outcomes; for example, in professional search and rescue tasks. Most disorientation cases result in anxiety, frustration and tardiness (Montello & Sas, 2006).

Struggle in reduced visibility and audibility environments

When interacting in ubiquitous environments, users have strictly limited attention capacity to spare for the computer interface. There are situations where users' visual and audio channels are occupied by other important tasks at hand or not available due to environmental factors, such as bad weather or a noisy environment. Hence, using today's visual-based GPS could be problematic. With an audio-assisted navigation system, an auditory display may conflict with other sounds in the environment (Tsukada & Yasumura, 2004)—and wearing headphones may prevent users from hearing ambient noise crucial to their safety during navigation. Hence, the use of visual and audio displays in some situations can be ineffective because dynamic characteristics of environments will affect users' attention, awareness and performance.

Loss of attention and situation awareness

Different types of journeys and tasks demand different levels of attention. Navigating in familiar areas demands less attention and could be automatic while navigating in unfamiliar environments demands much higher attention. Distractions in environments may affect user's attentional resources resulting in poor navigation performance. On the other hand, if users focus mainly on the instructions from the system, they will lose the sense of engagement with the environment resulting in poor development of cognitive maps and poor reconstruction of the environment through which they navigate (Leshed et al., 2008).

Implications for design

Human performance is limited (Gawron, 2008) and constrains visual-spatial thinking (Wickens, 1999). These constraints have implications for the design of alternative displays that better support users' understanding of spatial information and motion, and navigation task completion. Despite claimed and perceived benefits of visual-based navigation displays, system drawbacks impose very high levels of cognitive effort and mental rotation. Thus, our design goal is to create a display that: imposes fewer requirements for extensive transformations between frames of reference by the human operator; and allows the human operator to attain task performance with improved speed and accuracy.

Although there are limitations in conveying semantically rich information via the tactile channel, its characteristics and potential benefits provide opportunities for designing novel and useful user interfaces.

The next subsection will discuss using an alternative channel for the tasks in question.

1.1.3 Finding an alternative communication channel

Audio vs Haptic

In the previous subsection, we saw that visual-based navigation requires a high level of cognitive effort (Yao & Fickas, 2007) and when there are many frames of reference to be considered, the design of the system can be overly complicated (Wicken et al., 2005). Although vision may not be the optimal modality to present spatial information in some situations, we do use our eyes to perceive distinctive features in an environment.

Researchers and manufacturers realise these performance issues. As a result, some SatNav units provide alternative or supplementary verbal in addition to graphical and textual information; they are multimodal. However, the area of multimodality has not yet been fully investigated. Researchers and manufacturers have yet to define the optimal mixture of audio and visual information for different situations. There are problems such as the complexity in the association of functions with a number of modalities and modes available and the integration and dispersion of input and/or output streams from more than one sensory channel. Hence, if we assume that visual display, even with the addition of verbal instructions, is not ideal for presenting spatial information, we should seek an alternative one.

Among the five senses, there are two, auditory and touch, which may potentially be used as a substitute for the visual sense.

Auditory information may be provided as a series of verbal directions and an explanation of specific features, presented sequentially in a timely manner as users move along a route. However, with auditory displays, we must not forget that they could be varied in level of sound and sound quality. One system can provide supplementary synthesised speech or abstract sound (see Table 1.1). Researchers (Holland et al., 2002; Strachan et al., 2005; Warren et al., 2005; Jones et al., 2006; Wilson et al., 2007; Stark et al., 2007; Jones et al., 2008; McGookin et al., 2009; Tardieu et al., 2009) have implemented audio-based navigation systems which incorporated audio-feedback with GPS technology for pedestrian navigation. Field evaluation of Holland et al. (2002) and Strachan et al. (2005) did not provide promising results because the applications suffered from a lack of GPS availability and delayed response. Other researchers reported that sound could be used effectively as directional cues (Wilson et al., 2007), as navigational homing information to more easily locate landmarks and destinations (McGookin et al., 2009; Warren et al., 2005) and as orientation & confirmation signals (Tardieu et al., 2009; Rehrl et al., 2010). It is reported that sound used for turn-by-turn instructions is useful in reducing navigation time but may not be superior to visual maps as it did not yield significantly better performance compared to the visual-based one (Warren et al., 2005; Stark et al., 2007; McGookin et al., 2009).

Table 1.1 Representation format of different semantics via different senses

Sense	**Semantic rich**	**Semantically moderate**	**Semantically poor**
Vision	Text	Icon	Light
Audio	Speech	Natural sound	Earcon[4]
Touch	-	-	Tacton[5]

Furthermore, in some situations there is a chance that important *nonverbal* cues might be lost because they cannot compete with other sounds in the environment (Tsukada et al.,

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[4] The Earcons are abstract, structured synthetic tones that can be used to represent parts of an interface. The sound design manipulates timbre, pitch, register, rhythm, intensity and a combination of these attributes. See Brewster et al., 1999, 2002, 2003.

[5] Based on Earcons, the Tactons that are abstract, structured synthetic vibrotactile signals, are interface widgets constructed by synthesising tactile properties such as amplitude and frequency. See Brewster & Brown, 2008.

2004; Kahol et al., 2006). This scenario may be more serious if users were drivers of fast vehicles or attending to safety-critical tasks.

The other channel being considered as an alternative is touch. As Marston et al. (2006) compared tactile-based with audio-based navigation interfaces, it turned out users performed better with touch than sound. There is much evidence that navigation with touch is effective (Holland et al., 2002; Tan et al., 2003, Tan et al., 2005; Ternes & MacLean, 2008; Raisamo & Myllymaa, 2010; Elliott et al., 2010).

Tactile displays have the potential to be deployed as an alternative to conventional visual displays that help minimise transformations and cognitive demands. We are interested in investigating if the number of frames of reference involved could be reduced with tactile displays. We predict that at least two visual frames of reference can be reduced, the display and the control frames, which in turn will dramatically reduce the mental rotations that the human operator has to perform with visual navigation systems. Since tactile interaction uses the skin as a communication channel, input stimuli perceived via the skin are interpreted more directly without the intermediate processes of visual transformations between frames.

Tactile communication is also reported to work effectively in environments where there are different forms of noise and environmental constraints and when users' attention may be limited (Tan et al., 2003). In addition, many tactile systems, which can be fitted to various parts of the body, can be aligned well with the ego-trunk frame (e.g. Duistermaat, 2005; Erp et al., 2005; and Frey, 2007).

The next subsection will briefly describe the benefits of tactile interaction.

Benefits of tactile navigation

Research in tactile communication can be a promising area but it is still understudied. Aziz & Nicholas (2006) reported that only 1% of modality research is on the touch sense.

Researchers have reported that tactile guidance systems have successfully guided navigation with acceptable performance in different environments, e.g. forested areas (Duistermaat, 2005; Elliott et al., 2010), and urban environments (Frey, 2007; Erp et al., 2005), both in normal and extreme conditions.

Interaction based on touch may help overcome situations where visibility and audibility are limited (e.g. Erp et al., 2005; Tan, 2000) or not available at all (e.g. Marston et al., 2006;

Ross and Blasch, 2000), and in challenging environments such as a smoke-filled building or a crowded, noisy space.

A comparison between visual-based and tactile-based found that in normal walking conditions, the performance of both systems is equally good (Pielot & Boll, 2010). However, participants with the visual-based system experienced more collisions than with the tactile system. Elliott et al.'s (2010) study concluded that the tactile-based outperformed the visual-based one under conditions of high cognition and visual workload. In addition, it is reported that tactile feedback helps improve the speed of navigation in a situation when the moving map orientation mismatches with user's heading direction (Smets et al., 2008) and reduces errors and drift in a night-time context (Van Erp et al., 2003).

1.1.4 Current stage of research in tactile navigation and a proposal to further research in tactile pedestrian navigation

Current stage of research in tactile navigation

Research in navigation and wayfinding has a history dating back about 50 years. Researchers have since explored the cognitive (e.g. Weinstein, 1968), linguistic (e.g. Klippel, 2003), geographic (e.g. Wang, 2011), usability (e.g. Varden & Haber, 2009), and ubiquity (e.g. Tamminen et al., 2004) aspects of this very complex problem. From a human factor perspective, we have made progress in understanding the influence of environmental factors, individual differences, frames of reference, spatial information, route orientation and cognitive maps on navigation performance (Raper et al., 2007). However, navigation research is still considered a 'hard problem' (Raper et al., 2007). We need better technological advancements in positioning and a better understanding of psychophysics issues in relation to navigation tasks in the urban settings. Specifically, we need to understand relationships and effects among different locations on the human body with represented vibration patterns of spatial information and human cognitive mechanisms.

Tactile navigation research is in its early stage, dating back about 20 years. In addition to the above generic knowledge, researchers have since explored the modality-specific understanding on the cognitive (e.g. Wickens, 1980), biopsychology (e.g. Gallace & Spence, 2008), engineering (e.g. Brewster & Brown, 2004), representation (e.g. MacLean, 2008b), design (e.g. Van Erp, 2002) and proof of concept (e.g. Elliott et al., 2010) aspects of tactile interaction for navigation in normal and extreme conditions both for sighted and visually impaired users.

Much of the previous research emphasised the fundamental understanding and feasibility of touch as a means to communicate spatial information, mainly directional cues (e.g. Van Erp et al., 2005; Pielot & Boll, 2010a; Elliott et al., 2010).

A proposal to further research in tactile pedestrian navigation

The growth of the city offers new opportunities and introduces new problems to the urban population. With the ever-changing world, there is an ongoing trend of people moving from rural areas to live in the dense, crowded and traffic-congested space of the city for better options: where to go, what to do and what to see (Zuckerman, 2011). The number and the size of cities and cosmopolitans are continuing to expand too, with the rise of walkable cities (Zuckerman, 2011). Daily movement is a part of city living. We normally travel among places of work, home and hobbies (Chombart de Lauwe et al., 1952). These hobbies may regularly involve traveling to unfamiliar destinations. That is when the need for maps and tools to aid wayfinding in those places comes in.

In modern days, navigation among places is made easier by the availability of positioning technologies and the advancement of satellite navigation systems. We have learned from previous subsections that SatNavs, which were initially designed for vehicular navigation and mainly rely on the use of our vision, have imposed a few problems for their users despite their perceived usefulness. Researchers have proposed the use of touch as an alternative.

Whilst existing research demonstrated the feasibility of simple examples of useful tactile interfaces, there is a massive amount of research still to be done. This consists of the investigation of the *design* and *usability* aspects of a proper tactile navigation system for pedestrians and its *evaluation*. We have yet to find out, for example, how much tactile information a human can perceive, how to represent different levels of spatial granularity as well as users' acceptance of the wearable system and its practicality.

Hence, we propose further research in order to improve the level of usability, efficiency and effectiveness of future tactile pedestrian navigation applications.

One question that might be asked is: Why don't we first try to improve the quality of services of the visual-based display? We consider that the drawback of trying to add more information to visual representation could put an even greater load on the user's visual perception that they will concurrently use to observe the environment. We propose that touch has certain advantages. Touch should be used to replace visual and audio communication for this particular task, hence, freeing these resources to concentrate on other tasks (see Wickens et al.'s Multiple Resource Theory, 2005). Touch can provide the sense of presence and make interaction more engaging whilst maintaining a low level of cognitive capacity (MacLean, 2008b). Our skin contains the largest number of receptors, which can sense a vast amount of information through its greater bandwidth. The tactile research community believes that we could benefit from its richness and potential communicative capacity. However, this has not been fully understood.

Clear understanding regarding these open issues shall help with the design of suitable means for transmitting necessary spatial information for the tasks. Consequently, the user will be able to interpret the meaning of signals given appropriate stimulated locations and representation patterns. Advancing research in tactile interaction could be beneficial for the human computer interaction (HCI) community.

Research has shown that tactile interaction can enrich our navigation (e.g. Ross & Blasch, 2000). Nevertheless, much of the work focused on providing directional information (e.g. Van Erp et al., 2005), whereas in real life we use a few types of spatial information to aid wayfinding (Bradley & Dunlop, 2005). We are interested in finding out the thresholds of a number of information types and amount of information that can be provided via the tactile display.

There were reports on the positive effect of adding more types of information in visual navigation systems in terms of confidence and performance (e.g. Burnett et al., 2001). We are interested to see whether adding more types, if any, of information to the systems will hold analogous positive results. In addition, we expect to gain an understanding of the effect of represented signals on users' cognitive model, judgment, association and navigation behavior.

1.2 Research proposal

1.2.1 Scope and aims of the thesis

In urban canyons, navigating whilst simultaneously carrying out other tasks is considered a complex activity (Raper et al., 2007). Pedestrian navigation has been studied across a number of perspectives and disciplines. The scope of this thesis is concerned with the human factors perspective and an investigation of human computer interactive aspects associated with the design and evaluation of tactile pedestrian navigation systems. The thesis focuses on the use of tactile sensing as an alternative channel for output feedback.

A review of relevant literature revealed a lack of knowledge in pedestrian navigation and especially the cognitive problems caused by visual-based navigation displays. There is a major difference between vehicular and pedestrian navigation. As a result, SatNavs designed for use in an automobile do not accommodate requirements for navigation on foot under changing environments. Urban environments add complexity and a number of constraints to the tasks. In order to develop effective navigation guidance, we need to address a range of issues.

More specifically, the research presented in this thesis addresses: human tactile perceptual capabilities for pedestrian navigation tasks; the tactile perception capacity of spatial information; the effect of the form of wearable devices on tactile spatial perception; and the mapping between spatial information and its representation. Additionally, the nature of directional information and landmark usage in pedestrian navigation is empirically explored. The system evaluation will allow us to address the tactile-based navigation displays' usability and user experience issues.

1.2.2 Research questions

This thesis aims to investigate a pedestrian guidance system that provides directional *and* landmark information via the tactile sense. In order to explain an enhanced paradigm of touch communication at the human-computer interface for pedestrian navigation tasks, the prototype implementation and a series of empirical studies allow us to address the following research questions:

- *RQ1: What information types should the tactile navigation display provide to pedestrians?*
- *RQ2: How do pedestrians use landmarks for different navigation purposes?*
    - *RQ2.1 Do pedestrians use landmarks differently for the three different navigation purposes of commuting, questing and exploring?*
    - *RQ2.2 When do pedestrians use landmarks during navigation?*
    - *RQ2.3 What are the most important landmarks for each navigation purpose?*

- *RQ3: What is the effective form of tactile displays for pedestrian navigation?*
- *RQ4: How can we represent spatial information via the chosen device? Specifically:*
    - *RQ4.1 Which technique should be used to represent each type of spatial information?*
    - *RQ4.2 How to represent a few types of spatial information?*
- *RQ5: How does the tactile navigation system perform?*
    - *RQ5.1 Does the system help with different navigation purposes?*
    - *RQ5.2 Can tactile landmark representation "increase/help" with performance/confidence as in visual pedestrian navigation systems?*
    - *RQ5.3 Is there a problem with the transfer of frames of reference with tactile navigation displays?*
    - *RQ5.4 What are user acceptance and perceived usefulness (practicality) of the tactile navigation system?*

These research questions will be addressed in more detail in Chapter 2.

1.2.3 Research methodology and ethics

Research methodology

The research took an empirical approach. To develop the arguments in this thesis, we roughly followed the four processes for interaction design outlined by Sharp et al. (2011):

- Identifying needs and establishing requirements for tactile navigation systems
- Developing alternative designs that meet those requirements
- Building prototypes so that they can be assessed
- Evaluating what is being built throughout the process

We adopt both quantitative and qualitative methods to address both theoretical and practical perspectives of the design problems. We used a number of techniques: a questionnaire study, lab-based experiments and field-based evaluations. A questionnaire study allowed us to gather information on how pedestrians use spatial information, especially landmarks, during their course of navigation. Lab-based experiments allowed us to investigate human cognitive capabilities for spatial information and the effects of tactile signal properties and manipulation on the human perception of spatial data as well as to explore a number of potential tactile representation techniques for spatial data, specifically representing directions and landmarks. Field-based evaluations were deployed to address the design and usability issues of the system in a realistic setting.

Specifically for each study, we developed an understanding of a particular problem by reviewing existing designs and principles, and then carefully designed an empirical study built upon our developed insights. A prototype was built and systematically evaluated. These systematic studies provide a theoretical explanation of why one condition was different from the other. We also discussed alternatives. We drew conclusions from each study that fed into the next.

Research ethics

For research ethics, we strictly followed the University of Bath's Institutional Code of Ethics[6] which requires each department to have a local code of ethics (Watts, 2011). The Department of Computer Science Local Code of Ethics is expressed as a 13-point checklist (see Appendix 7).

Specifically, for any empirical study involving participants, we:

- Prepared a modified 13-point Ethics Checklist – all questions answered with specific study information (see an example in Appendix 8);
- Discussed the answers and the description of each study with Dr Eamonn O'Neill (who supervised the entire research project) ;
- Had the final Checklist approved by the Department of Computer Science's Ethics committee member, Dr Leon Watts, prior to running each study.

Once the Checklist was approved, we prepared related documents including an informed consent to participate, an overview of the experiment and experimental instructions (see examples in Appendix 9). Other details on codes of practice and procedures are described in Appendix 10.

1.3 Research contributions and novelty

This thesis focuses on pedestrian navigation tasks and investigates how to support them with a new form of interaction through the touch sense that may help solve existing problems occurring with visual-based navigation systems.

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[6] http://www.bath.ac.uk/vc/policy/ethics.htm

The thesis makes two contributions: a theoretical and a practical contribution. Addressing the first two RQs: *RQ1: What information types should the tactile navigation display provide to pedestrians?* And *RQ2: How do pedestrians use landmarks for different navigation purposes?* – we make a theoretical contribution. The contribution comes in the form of limited sets of spatial information that should be provided by any assistive navigation systems. These contributions act as part of the basis we use for the design of our practical studies.

Our attempt to answer *RQ3: What is the effective form of tactile displays for pedestrian navigation?* and *RQ4: How can we represent spatial information via the chosen device?* allows us to make a practical contribution. Through the attempts to understand the thresholds of tactile output channels on the human body (i.e. location, patterns, and frequency level) in relation to human perception and information representation issues, we elicit requirements and suggestions for the design of our prototype. These requirements were then carefully analysed through lab-based evaluations. The findings from lab studies identified appropriate forms of wearable device and developed our understanding of the capacity of a human's tactile sensory channel for conveying spatial information. This contribution is delivered in the form of heuristics for the design of tactile navigation displays: wearability, body sites' sensitivity, suitable direction concepts, the enrichment of route directions with landmarks, the amount of training associated with the use of the display, and a representation technique for each type of spatial information.

Dealing with the fifth *RQ5: How did the tactile navigation system perform?* – we also make a practical contribution. RQ5 contains four sub RQs regarding the practicality of the system in real world environments. Through field-based evaluations, we have established evidence for usability and user experience requirements of a unimodal tactile display. This contribution is provided in the form of a number of answers synthesised through careful consideration of the experimental results. We provide designers with performance-related and qualitative data as guidelines for the design of tactile feedback at the human-computer interface.

The thesis contributions are mainly in the domain of location systems and tactile interface design within the field of HCI. Whilst we focus on the domain of interaction design from the perspective of HCI, the thesis is also advantageous to the field of land navigation systems. Other related domains such as psychology and biopsychology could benefit from the findings of this research.

1.3.1 Research novelty

Chapter 3

In 2007, we compared the two most popular wearable tactile torso displays for directional information: the belt and two sizes of the back array. Results demonstrated that: between the belt and the array, the former afforded significantly much better performance; between the two sizes of the array (50mm and 80mm), the larger array size allowed participants to perform much faster and much more accurately. We then replicated Van Erp & Duistermaat's (2005), and Elliott et al.'s (2006) experimental design but moving the evaluation context to an urban landscape. Our field evaluation corroborated the results of the original studies that had evaluated the system in a forested area, showing advantages for the tactile display over the visual display in urban canyons, thus supporting the MRT and Prenav predictions[7].

Chapter 4

In 2009, we published three sets of landmarks (reported in Chapter 4) that are important for different navigation purposes. The lists are novel because they were empirically gathered from urban spaces at a global scale and systematically classified by different navigation purpose.

In 2010, we investigated how to represent two important spatial information types, direction and landmark, with tactile representation techniques. Our study suggested that a single-actuator and a dual-actuator technique should be used to represent direction and landmark respectively. The planning, execution and results from a lab-based study, reported in Chapter 4, confirmed the effectiveness of the Choreme[8] and Dual Coding[9] theories.

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[7] Both theories predicted performance advantage when information is presented to a less taxed sensory channel, i.e. touch.

[8] Eight egocentric directions

[9] Use of labels and images to improve learnability

Chapter 5

In 2011, we evaluated our hybrid[10] tactile-based navigation system, TactNav, in the field. Similar to Chapter 4, the planning, execution and results from a field-based study, reported in Chapter 5, confirmed the effectiveness of Choreme[11] and Dual Coding[12] theories. Similar to the results of the field study reported in Chapter 3, our field evaluation's performance data and observations, reported in Chapter 5, fully confirmed the MRT and Prenav theories that performance advantage can only be achieved if a tactile display is intuitively comprehended. In the hybrid system's evaluation, our participants had to learn to remember arbitrary landmark signal patterns. This made tactile communication less intuitive (in comparison to the more intuitive tactile directional signals).

1.4 Structure of the thesis

1.4.1 PhD research map

Figure 1.1 demonstrates the structure of the thesis and how each chapter contributes to our research questions.

Chapter 2 reviews research in the domain of tactile navigation and relevant adjacent areas. Chapter 3 investigates the design and use of a tactile guidance system to provide *directional* information. Chapter 4 tackles the issues of *landmark* usage and their representation. Chapter 5 draws the thesis work together, reporting a prototype system that has been developed and evaluated in an urban setting. Chapter 6 summarises our research contributions, notes limitations, and discusses opportunities for future work.

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[10] The system provided both direction and landmark information.

[11] Eight egocentric directions

[12] Use of labels and images to improve learnability

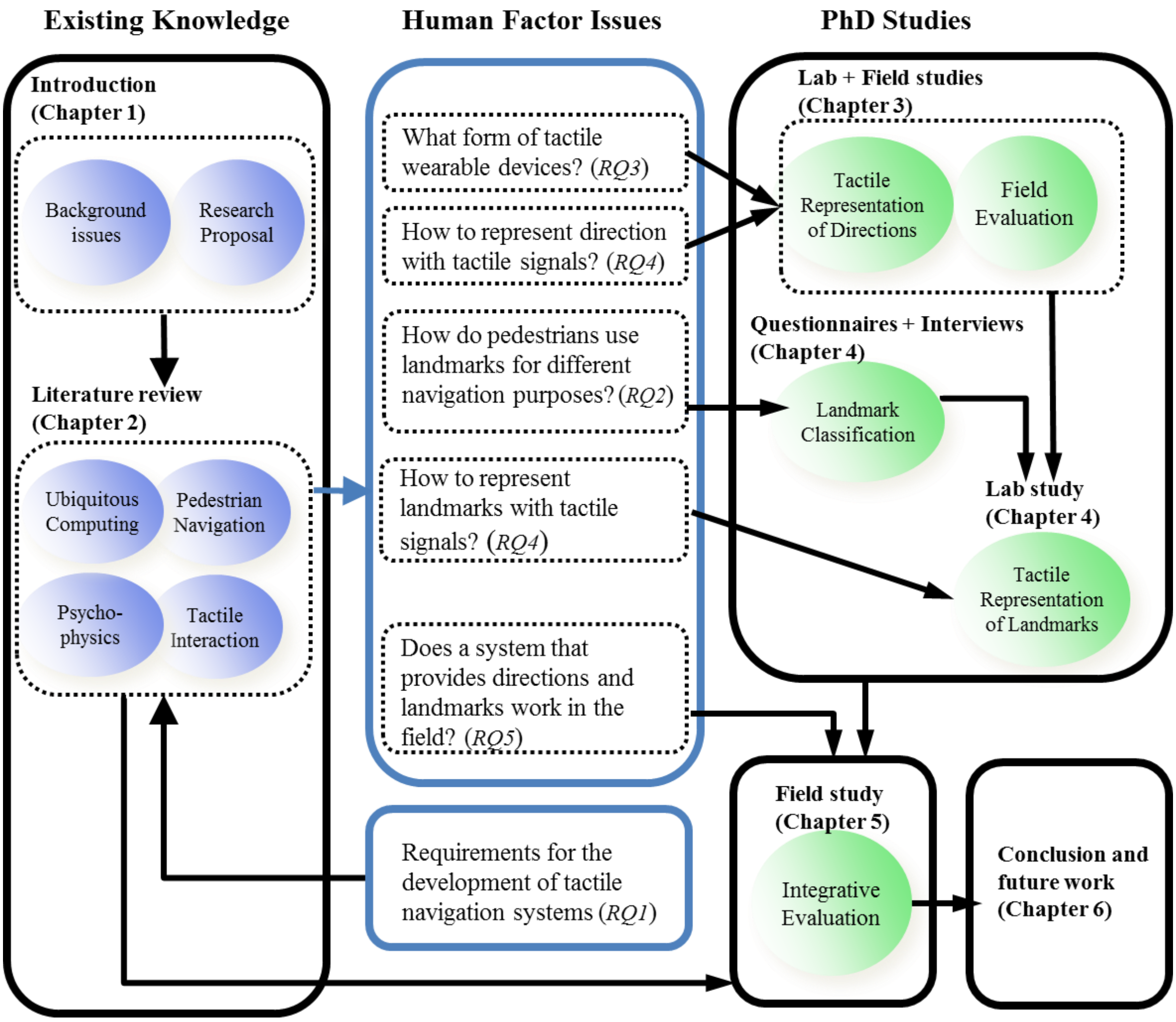

Figure 1.1 Structure of the thesis

1.4.2 Thesis outline

Chapter 2 – Literature review

Chapter 2 sets the scene for the rest of the thesis by visiting a rich list of literature crucial to the establishment of the research problems and our research proposal. To assist with investigating these problems and developing the innovation, the chapter examines human factors issues (perception, cognition, and psychophysics), ubiquitous computing and environmental issues (the nature of urban canyons, environmental constraints, mobile users' characteristics and behaviors including their navigation strategies) that affect navigation performance. We then examine physical attributes of tactile signals and potential representation approaches in relation to spatial information. We give details of previous work in tactile interaction design. Towards the end of the chapter, we present our proposal in light of design and usability and user experience issues, as well as reporting on the research approach taken to address RQ1 (*what information types should be* *displayed*). In response to RQ1, the chapter introduces a limited set of spatial information types necessary for navigation completion including: direction, landmark, orientation, and confirmation cues.

Chapter 3 – Investigation into tactile directional display

This chapter builds upon chapter 2's set of spatial information types necessary for navigation completion. The primary focus of this chapter is the investigation of displays of tactile *directional* information. The chapter aims to find out the more effective form of display between the two most popular types of wearable tactile displays: a back array and a waist belt. Each type has its proponents and each has been reported as successful in previous independent experimental trials. The chapter reports results from direct experimental comparisons which indicate that the tactile belt allowed participants to perform significantly faster and more accurately than the tactile back array. Another conclusion that can be drawn in this chapter is the representation technique, i.e. absolute-point vibration, for directional information. This lab-based experiment addresses RQ3 (*the form of wearable device*) and RQ4 (*how to represent directional information*).

We then took the waist belt device to develop a prototype system that provides directional and confirmation cues. It was evaluated in an urban environment, along with a visual mobile maps application. The second part of this chapter reports results of a comparison study as well as discussing performance-related issues. Results indicated that users' performance with the tactile-based navigation was equivalent to that of the visual-based system in terms of accuracy while route completion time was significantly faster with the tactile-based navigation. This field-based evaluation addresses RQ4 (*how to represent confirmation information*), and RQ5 (*system performance*), specifically RQ5.1 (*system for quest navigation*).

Chapter 4 – Investigation into landmark displays

Chapter 4 builds upon Chapters 2 and 3. The chapter reports results from two empirical studies: a survey research on landmark usage and a lab-based experiment on tactile landmark representation.

The first section builds upon chapter 2's set of spatial information types, focusing on the use of landmarks for different navigation purposes. We achieve this by means of an online survey and face-to-face interviews. The chapter provides a classification of important landmarks or landmark types used in the urban context, both local and worldwide. This empirical study addresses RQ2 (*classification of landmark for different navigation purposes*)

The second section reports a study that compared two tactile display techniques for landmark representation using one or two actuators respectively. The single-actuator technique generated different vibration patterns on a single actuator to represent different landmarks. The dual-actuator technique generated a single vibration pattern using two simultaneous actuators and different pairs of actuators around the body represented different landmarks. Results showed that users performed equally well when either technique was used to represent landmarks alone. However, when landmark representations were presented together with directional signals, performance with the single-actuator technique was significantly reduced while performance with the dual-actuator technique remained unchanged. This lab-based experiment addresses RQ4 (*how to represent landmark information*).

Chapter 5 – A field evaluation of tactile displays for pedestrian navigation

Chapter 5 focuses on the system design, development, and evaluation of our prototype tactile navigation display, based upon requirements developed throughout the thesis (i.e. results from Chapters 2-4). It was used to gather performance-related data regarding practical use of the tactile navigation display in urban settings. The system being evaluated provides four types of spatial information: direction, landmark, destination and confirmation cues. The chapter reports a number of usability and user experience issues and discusses navigation stages in tactile wayfinding in comparison with those in visual wayfinding. This field-based evaluation addresses RQ4 (*how to represent a few types of spatial information*), and RQ5 (*System performance*).

Chapter 6 – Conclusion and future work

This chapter concludes the thesis, summarizing the outcomes, limitations and contributions. This allows us to identify future research topics in the domain of tactile pedestrian navigation.

Yet the best pilots have need of mariners, beside sails, anchor and other tackle.

(Ben Jonson, 1641)

Chapter 2 Literature Review

This chapter intends to visit related concepts and prior research in tactile interaction design. The thesis focuses on how to represent spatial information via the tactile channel and provides suggestions for the design and implementation of tactile pedestrian navigation systems. In order to appropriately explore the interactive aspects of the tactile-based system design, we need to understand underlying physiological and psychological theories such as how the human body can deliver great potential for the tactile-based systems. In addition to such understanding, we need to look into practical knowledge on characteristics of ubiquitous environments and mobile users, existing assistive technologies and their role, as well as tactile interfaces and wearable devices that provide a foundation for planning and assessing our studies.

The organisation of this chapter is as follows. The first part describes characteristics and constraints of ubiquitous environments and the nature of navigation tasks as well as information requirements. The second part discusses role of technologies in navigation and problems with existing assistive navigation technologies. In the third part, related research in the domain of tactile interaction design is reviewed. In the fourth part, we introduce the basis for our research program and propose opportunities to advance tactile research in the pedestrian navigation domain. The final part summarises the chapter.

2.1 Pedestrian navigation in urban environments

The key prerequisites to designing effective pedestrian navigation systems are to understand characteristics of spaces through which pedestrians navigate, the nature of the tasks, and the information requirements. This section attempts to explain how pedestrians navigate in urban environments regardless of assistive navigation technologies. It divides into three subsections. The first subsection describes characteristics of urban environments that affect pedestrians' performance and behavior. The second subsection explains functional distinctions of wayfinding tasks in urban spaces. And the third subsection clarifies information requirements for navigation tasks.

2.1.1 Urban environments

In the real world, there are operating parameters that fluctuate which may affect pedestrians' attention to navigation tasks. These parameters include: noise level and their fluctuations, light level and their fluctuations, weather condition, number of people in the space, relationship between people present and activities (Zacharias, 2001).

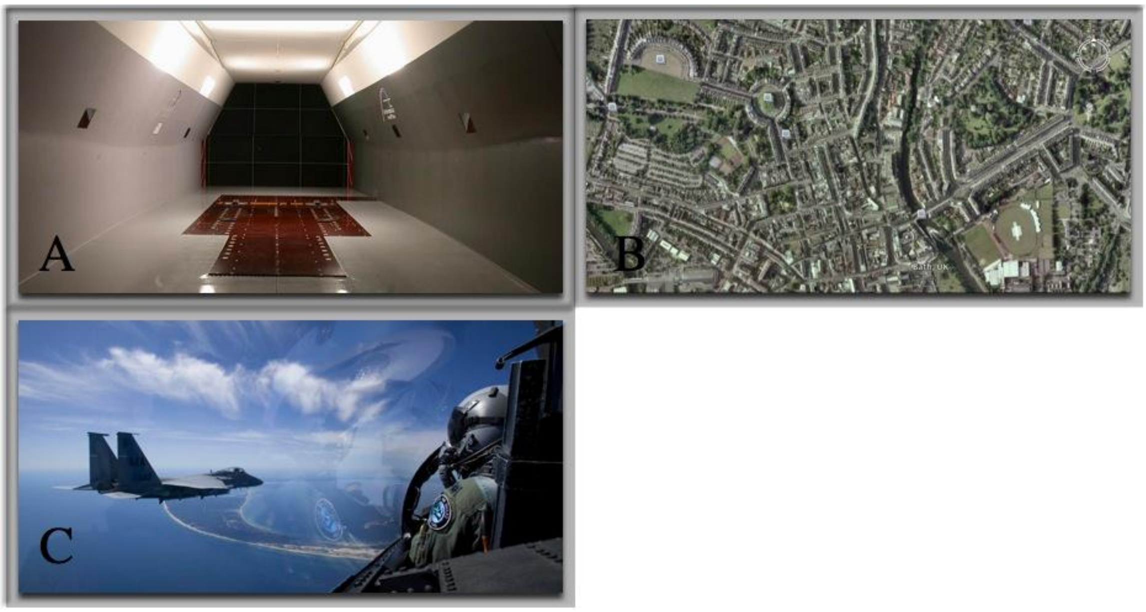

Figure 2.1 Different types of space classified by size (Darken & Sibert, 1993): A – A small world; B – A large world; C – An infinite world. (Source: Google images)

Navigating in urban environments could be problematic because their characteristics make navigation different from navigation in other kinds of spaces. According to Darken & Sibert's (1993), urban areas can be considered as *large, dense* and *dynamic* spaces[13] (see examples of different types of spaces in Figures 2.1 - 2.2). The combination of the three characteristics makes navigation in such spaces very complex. Carter & Fourney (2005) stated that the structure of environments plays a significant role in navigation success. An area that has distinctive architectural structure and contains visually obvious features and landmarks affords the ease of wayfinding (Montello & Sas, 2006). On the other hand, built environments that have more regular patterns, such as grids, lines or symmetric shapes (while natural landscapes have more curved and asymmetric shapes) may cause confusion

[13] Spaces being classified by *size*, they can be small, large and infinite; by *density*, spaces can be divided into three types: sparse, dense and cluttered; by *level of activity of objects within spaces*, they can be considered as static or dynamic worlds (Darken & Sibert, 1993).

leading to navigators becoming disorientated and eventually lost. In other words, people's performance and behavior in navigation are affected by the city's structure, route qualities and landmark orientation (Millonig & Schechtner, 2006).

Figure 2.2 Different types of space classified by density (Darken & Sibert, 1993): A – A sparse world has large open spaces; B – A dense world is characterised by a relatively large number of objects and cues; C – A cluttered world. (Source: Google images)

Zacharias (2001) added that city structure has a direct effect on route preferences and the level of ease in navigation. Types of activities play a significant role in engaging in the environment. For example, in a recreational context, crowding can be attractive such that pedestrians may be drawn towards the crowd. However, in other circumstances, the crowd is best avoided.

Artificial qualities of space including sound and light are also important. For example, the level of artificial lighting can have a substantial influence on route selection after dusk. In fact, lighting patterns have a major influence on perceived friendliness and safety of the area (Zacharias, 2001). Furthermore, such a low light condition can reduce visibility and the user may miss an important turning point resulting in getting lost. Navigators walking at night feel more vulnerable and are more alert to strangers (Melbin, 1978). The level of sound can have a significant effect on peripheral attention. It is found that people walk faster in an area with high traffic noise; as a result, they could remember few details in that environment (Korte & Grant, 1980; Franěk, 2012).

Other unexpected environmental factors such as bad weather may undermine task performance. In some extreme conditions such as navigating a building filled with smoke or an environment filled with fog, relying on the visual perception may lead to safety-critical setback. These diversities in the environments, which affect pedestrians' visibility and audibility, add more complexity to the large, dense and dynamic spaces.

2.1.2 Navigation purposes

As our thesis aims to better support navigation in urban spaces, it is necessary that we understand the nature[14] of the tasks that travellers must continuously coordinating route planning, wayfinding and locomotion skills thereby balancing their perception, cognition and motor behavior in order to navigate effectively. In this subsection, we would like to further describe the different functional distinctions of wayfinding tasks. Researchers (Allen, 1999; Millonig & Schechtner, 2005) reported that generally pedestrians have three different purposes including commute, explore and quest.

Commute – refers to the journey between two familiar places. The wayfinding process for this type is automatic and highly related to routinised behavior and, consequently, requires very little attention and cognitive effort. Commuters are found to be able to select alternative routes between two points when needed. Travellers deploy methods known as repetition of locomotion and piloting to reach the destination. Repetition of locomotion involves repeating learned motor patterns along a route. Piloting involves landmark-based navigation. Specifically, they follow the temporal-spatio sequence of landmarks along the route in an automatic manner.

Explore – refers to the journey between places in unfamiliar territory for the purpose of learning about the surrounding environment, e.g. to discover new places and new routes linking them. The wayfinding process requires a high level controlled processing of attention and strategic cognitive effort. A combination of three wayfinding methods is required to succeed in the task: piloting, path integration and navigation by cognitive map. (For an explanation of piloting, see in Commute). Path integration is a technique involving the process of updating one's current location with reference to a point of origin in order to find the way back. Navigation by cognitive map is a technique in which a traveller relies on an internal representation of a set of interconnected places that include their locations,

[14] We have described the nature of navigation tasks earlier in Section 1.1.1.

distances, directions among places. A traveller uses information gained through a cognitive map for orientation.

Quest – involves travel from a familiar place of origin to an unfamiliar destination, a place known to exist but a traveller has never visited before. The wayfinding process requires a similar effort to those of exploratory purpose. A combination of two wayfinding methods is required to succeed in the task: piloting, and navigation by cognitive map. (see explanation above)

As we can see that each of these navigation purposes requires different set of skills and types of information, understanding the differences would dictate how the design of tactile-based navigation systems should be realised to accommodate these three purposes.

2.1.3 Information requirements for pedestrian navigation tasks

The final part of prerequisites for the designing of effective systems is to understand tasks' information requirements. In pedestrian navigation, Bradley & Dunlop (2005) has reported that pedestrians use several types of important information and cues in space to help reach their destination (see Table 2.1).

Table 2.1 Classes of Contextual Information Used by Sighted and Visually Impaired Users. (Bradley & Dunlop, 2005)

Class of contextual information	Example	% Used by sighted users	% Used by visually impaired users
1. Directional	Left/right, north/south	37.4	30.1
2. Structural	Road/Monument/Church	11.5	20.1
3. Environmental	Hill/river/tree	1.6	2.9
4. Textual-structural	Greaves Sports/ Border's bookshop	9.9	1.2
5. Textual-area/street	Sauchiehall St.George Sq.	15.6	2.7
6. Numerical	First/ second/ 100 m	5.0	7.5
7. Descriptive	Steep/tall/red	10.8	23.8
8. Temporal/distance	Walk until you reach...or just before you get to...	8.2	5.1

In a related study, May et al. (2003) established that to reach their destination, both sighted and blind users depend mainly on directional information, which is used at key decision points (e.g. at turns). Additionally, they may use landmarks to identify points en route and street names to confirm their navigation decisions. Distance is used very rarely due to a slow moving speed (hence, not necessary). Researchers noted that the use of information can be classified into two levels: primary and secondary. Primary information is defined as information that a pedestrian *must* receive in order to navigate successfully or to identify points on route (including landmarks, road type and junction name). Secondary information is defined as information that a pedestrian does not necessarily need but which aids navigation to a certain level (including street name and distance).

Based on both studies (May et al., 2003; Bradley & Dunlop, 2005), we can conclude that directional information and landmarks are primary to navigation success for both sighted and visually impaired users. We explain the two types in the next subsections.

Direction

Direction is the information contained in the relative position of one point with respect to another point (Klippel, 2003). It can be either relative to the body (i.e. egocentric) or absolute grounded in the world (i.e. allocentric or cardinal directions).

Egocentric directions are defined with respect to some part of the person being nodal point of the eye, the retina, the head or the body (Howard, 1993), including for example the directions of left, right, back, and forward. On the contrary, allocentric directions are independent from one's location, instead linked to a reference frame based on the external environments (Howard, 1993), including for example the geographical directions of north, south, east and west. Directions appearing on the maps are allocentric (Tan, et al., 2003). As demonstrated in Table 2.1, pedestrians use both directional concepts during their journey (Bradley & Dunlop, 2005) and across all three navigation purposes (Allen, 1999; Millonig & Schechtner, 2005).

Landmark

Landmarks for human navigation can be any objects or places that are stationary, distinct and salient, which serve as cues for active navigation (i.e. wayfinding) and build a mental representation of the area (Millonig & Schechtner, 2005).

Any object can be perceived as a landmark if it is unique enough in comparison to the adjacent items (Millonig & Schechtner, 2005). Local landmarks are either used at decision points, where a reorientation is needed, or they serve as route marks, as confirmation for being on the right way. Distant landmarks, like mountains or large buildings, fulfill a compass-like role and are used for an overall guidance, as they can be seen from many points and greater distances. (For more explanation on roles of landmarks, see Appendix A2.5)

Once one experiences a fixed sequence of landmarks and their locations in traversing a route, one forms route knowledge. Eventually, one will have an abstract understanding and an integrated knowledge of several routes; this is called survey knowledge of the surrounding area.

Grabler et al. (2008) have classified landmarks into 3 categories: *semantic*, *visual* and *structural*. Semantic landmarks are defined by their importance to pedestrians, e.g. their meanings are personal. Visual landmarks are defined by their visual appearance such as façade color, shape complexity and building height. Structural landmarks are defined by their location and their role in the surrounding environment, such as a building at an intersection or a square like Trafalgar in London.

Humans use different types of landmarks for different navigation purposes (Sorrow & Hirtle, 1999). According to Allen (1999), human wayfinding, which may need some kind of guidance, can be categorised into three types: traveling to a familiar destination (*commuting*); traveling to an unknown destination (*questing*); and exploring the area, which might or might not involve visiting important landmarks (*exploring*). According to Sorrow & Hirtle, (1999), visual landmarks are used for navigation to a familiar destination; structural landmarks are used for navigation to an unfamiliar destination; and both types are used for exploring the area.

Landmarks are picked by their saliency, subjectively and depending on mode of navigation. In other words, they are picked subjectively particularly in learning and recalling turning points along the paths (Sorrow & Hirtle, 1999). They help with the signaling where a crucial action should or should not take place at points on a route where changes in direction are likely to occur, helping to locate another less visible landmark.

It is vital to note that only good landmarks are useful (Sorrow et al., 1999) and using bad landmarks lowers navigation performance (May & Ross, 2005). Hence, it is important to clarify characteristics of good landmarks.

According to researchers, (May et al., 2001; Burnett et al., 2001; May & Ross, 2006), factors that constitute good landmarks include:

- The landmark itself (e.g. its visibility and its uniqueness – whether it can be easily and unambiguously described)
- The general setting of the landmark (e.g. the extent of visual clutter of the background)
- The exact location of the landmark (e.g. proximity to a turning and the ease with which the position allows identification with a turning point)
- The existence of other objects (e.g. whether other similar objects are nearby that may be confused with the intended landmark)
- The existence of other information sources (e.g. whether there are any other information sources that can be used in preference to the landmark)
- The navigator characteristics (e.g. the familiarity that a navigator has with that particular landmark)
- The environment (e.g. whether it is night or day; foggy or clear).

2.2 Role of technologies in navigation

In the previous section, we have described how people navigate in urban spaces. In this section, we would like to revisit the role of technologies in navigation and pinpoint navigation problems occurred while using existing navigation technologies.

For many thousand years, humans have developed techniques and technologies[15] to support our navigation tasks. Using these technologies, especially maps both paper-based and electronic, we mainly rely on our vision and auditory senses and use different navigation strategies such as taxon[16] and route[17] navigation (Millonig & Schechtner, 2005), which requires us to constantly matching the real world with the map as well as performing mental orientation when directions change. Specifically, sighted and able pedestrians navigate with any form of maps or visual guidance, gather information about the world through their eyes and ears when moving along routes, interpret perceived information

[15] Please see Section 1.1.1 for the list of technologies and Glossary for explanation.

[16] An individual moves towards a visible cue, which leads to the arrival point (Redish, 1999).

[17] An individual associates directions with visual cues, e.g. turn left at the church (Redish, 1999).

about the world in comparison with information seen on the map. Navigation success depends on their ability to perceive and interpret information and then direct their movement towards intended destinations.

To aid navigation within complex urban spaces, travellers may deploy electronic maps, i.e. SatNavs. Somehow using such systems could be problematic because the building's height may block satellite signals. Specifically, both pedestrians and vehicular users who navigate with SatNavs in urban areas will suffer from limited availability and accuracy. Wang (2011) reported that pedestrians using satellite technologies will suffer more than vehicular drivers in that they will receive less signal strength. Pedestrians move along the side of the road next to those buildings while drivers are situated in the middle of the road.

Most SatNavs provide spatial information via visual and audio perception channels. Users can choose to receive information simultaneously or switch to the preferred channel according to the current situation. Information from both modalities complements each other during interaction. Although the use of digital mobile technologies was reported to help decrease a problem with geocentric data reading (Chandrasekar, 2008), research in SatNavs pointed out that their use impedes an individual's understanding on survey knowledge[18] (i.e. overall understanding of spatial layout of the environment) and disengages such an individual from the environment because she/he has to concentrate on the turn-by-turn route instructions (Leshed et al., 2008; Aslan et al., 2006). Additionally, there are other problems with these technologies. For example, screen visibility could be poor if one tries to use it in a very bright light condition. For more discussion on advantages and disadvantages of visual-based assistive technologies, see Section 1.1.2. Despite the system' high cognitive demand and technical limitations[19], SatNavs are popular among urban travellers (Chandrasekar, 2008).

Research in mobile guides has found that using SatNavs in operational environments could be challenging because mobile users will be interacting more with the real world than with computers and they are always multi-tasking (Tamminen et al., 2004). Specifically, navigating tasks restrict multitasking ability because users are occupied by activities that

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[18] Survey knowledge represents knowledge about interconnections between discrete features of locations and routes of the area known by the individual (Goldin & Thorndyke, 1983).

[19] Discussed earlier in Section 1.1.2.

demand a high level of attention and cognition (i.e. required to pay attention to the environments, perform route selection, checking timetable etc.) (Tamminen et al., 2004). Furthermore, interactions with computers are rapid and driven by contextual factors such as weather and the appearance of surrounding objects (Rodden, 2007). The requirement for attention and cognition may even get higher for unexpected situations such as getting lost or getting closer to the destination. Consequently, they have strictly limited attention capacity to spare for the computer interface and for other tasks.

As we seek to understand how pedestrians use visual-based navigation application to support their tasks, there has been no documented model on pedestrian navigation with assistive technologies. Instead, we found two navigation models proposed by Zhai (1991) and Burnett (1998), both focus on driving tasks with help of visual-based assistive technologies. We document both models here because they are of particular interest to this thesis. We hope that the models, albeit possibly inconsistent with those for pedestrians (Gaisbauer & Frank, 2008), can be used to guide our investigation, which eventually facilitates the development of better assistive systems.

2.2.1 Navigation models

In early navigation models (e.g. see Mark, 1989), the conceptual view of navigation models is composed of processes of route planning, instruction generation and vehicle control. Zhai's (1991) behavioral model is a more elaborate one which has accounted for the driver, assistive technology, vehicle and the environment (see Figure 2.3). The model describes difficulties drivers have to encounter during a course of navigation using an assistive technology such as a SatNav. To make a navigational decision, one has to divide attention and take into account information from the environment, the system and own cognitive map. There is no further breakdown of navigation tasks in Zhai's model.

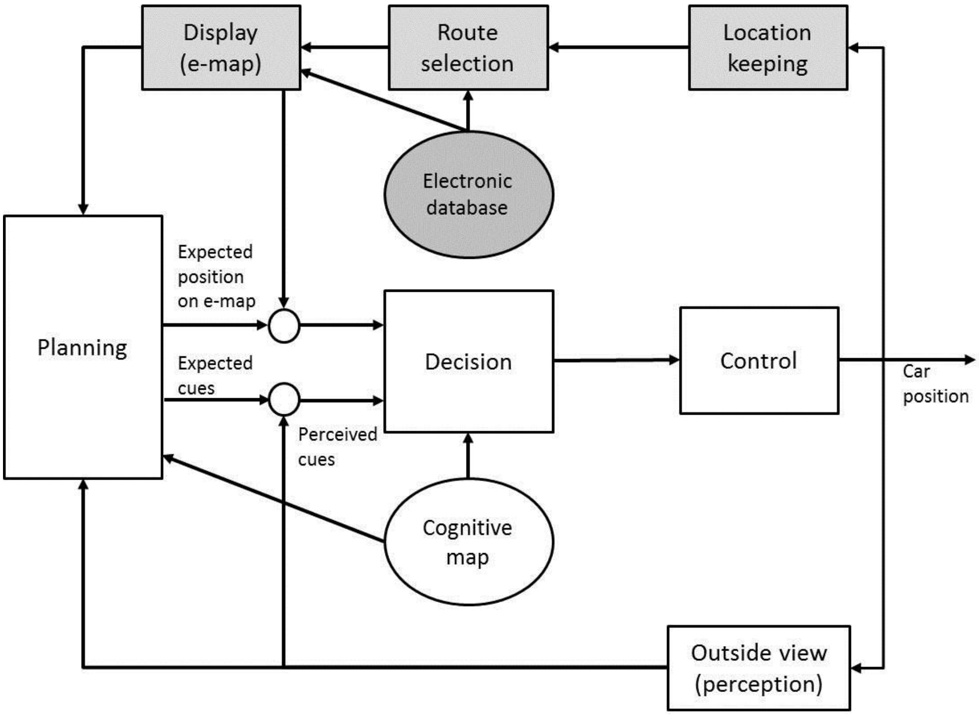

Figure 2.3 Behavioral model of navigation task (Source: Zhai, 1991). Transparent boxes are human activities; Shaded boxes are system functions; Transparent and shaded circles are human and system resources respectively

Then in 1998, Burnett proposed a model of stages of navigation (Figure 2.4). In his view, navigation is conceptualised as a continuous task across the whole timeframe. It starts with trip planning then a navigator sets off to reach an intended destination. During the course of navigation, a person carries out five activities: previewing next manoeuvre, identifying direction, confirming navigational choice, seeking confidence and orienting oneself with the environment and in relation to the destination.

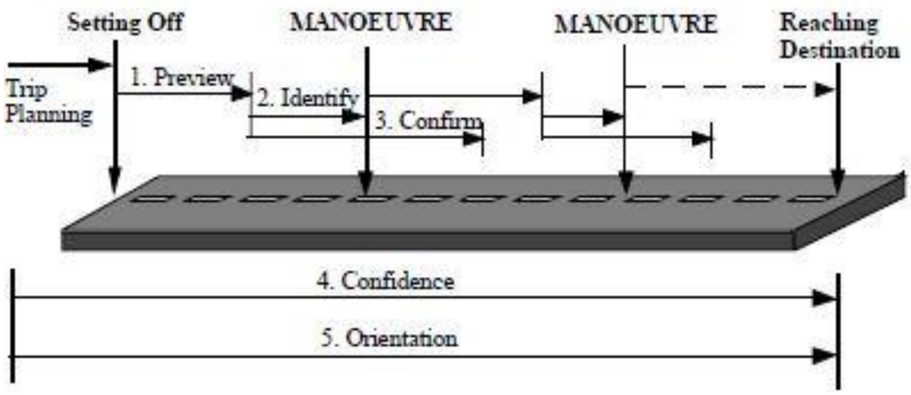

Figure 2.4 Burnett's stages of navigation tasks (Source: Burnett, 1998)

In comparison to Zhai's model of behavior, Burnett's stages of navigation tasks incorporate a temporal description that enables the drivers' goals to be assigned to each stage of the navigation tasks (see full list of stages' goals in Burnett, 1998, p. 178).

2.2.2 Navigation errors

We have mentioned earlier that using visual-based technologies could lead to frustration and navigation errors. In this subsection, we describe related research that has looked into navigation errors and pinpoint their causes and effects.

Raisamo & Myllymaa (2010) indicated that there are three kinds of problems that make pedestrian navigation difficult: orientation errors, lack of confirmation of direction and lack of information about the remaining distance to be covered. In a thorough study by Owens & Brewster (2011) in a paper map-based visual navigation context, they suggested that sources of errors in navigation and wayfinding could come from three things: map, navigator and environmental errors. Specifically, the maps could be incorrect; navigator could read the map incorrectly or move incorrectly; or the environment could have changed (either temporarily or permanently) since the map was produced.

Results from their study specify the detailed level of these errors. It shows that there are 10 common errors (resulting from a mix of three main error types above). The ratio of error sources for Map:Navigator:Environment is 4:5:1 respectively. These errors include:

1. Map - no path join (omit parts of path),
2. Map – no (full) path,
3. Map – path not clear (obscured by other features),
4. Map – feature missing,
5. Navigator – missed environmental clue (not seen),
6. Navigator – distance misjudgment,
7. Navigator – disoriented,
8. Navigator – choice hesitation (slow/stop),
9. Navigator – wrong path,
10. Environment – redundant choices (several paths to the same destination)

The progression from paper maps to electronic ones presents additional challenges. The Royal Institute of Navigation (RIN) made a comment in 2011 that people who navigate with electronic systems make mistakes in navigation because the current performance of positioning services (GPS) deployed by most SatNavs is not quite accurate (approximately 50-80 meters error) and the map data used by the system is quite poor in quality.

These technological setbacks contribute to users' confusion and errors. Each of these errors causes different effects including inefficient route selection, confusion, misjudgment, disorientation resulting in slowing down, stopping navigation or making wrong turns and eventually getting lost.

According to Owen & Brewster (2011), people used more than one tactic to overcome each navigation error. They defined seven common tactics including: (1) backtracking to a known point, (2) exploring the surrounding area to gain more information, (3) care, (4) resetting the map, (5) planning ahead, (6) rerouting and (7) make a quick best guess (not optimal). Statistically, the first two are the most common ones used by most navigators.

The implication from these studies suggests that if we are able to (1) eliminate controllable mistakes such as map errors and (2) provide functionalities that prevent and accommodate potential navigation mistakes, potential errors in navigation could be reduced and performance should be improved. However, improvement of the map and positioning accuracy are beyond the scope of our study.

As our thesis aims to seek an alternative system that better accommodates navigators, the next section, we describe previous work in tactile navigation displays on how it has been developed and used to ease or solve problems founds in visual navigation.

2.3 Tactile navigation aids

2.3.1 Unimodal tactile navigation systems

One may argue that to solve utility and usability issues of visual-based navigation system, multimodal interaction (a paradigm that combines several perception senses) should be adopted. However, problems with multimodality are recognised. The high-level problem with multimodality includes the complexity in the association of functions with a number of modalities and modes available. The lower-level is that multimodal interaction deals with the processing of more than one stream of input and/or output from more than one sensory channel. There is a need to integrate these inputs (*modality fusion*[20]) before the

[20] Modality fusion refers to the process of combining multiple modality input streams into a single result which is modality-free but rich in semantic.

system can process and disperse these outputs (*modality fission*[21]*)* back to the users. These issues are not yet fully understood. There is also the issue of conflicts between semantically overlapped inputs/outputs. In addition, as we learned earlier that the perception via one sense can affect another, we cannot be certain if the effect would not decrease the performance of the main task attended by the intended modality.

In navigation, a lack of users' attention on moving through the environment can lead to accidents (Holland et al., 2002; Tsukada et al., 2004). The use of audio-based navigation systems was reported to be successful (Loomis et al., 2001; Holland et al., 2002; Fickas et al., 2008; Jones et al., 2008; Tardieu et al., 2009; Rehrl et al., 2010;). However, it can be difficult hearing an auditory display when it conflicts with the other sounds in the environment (Tsukada et al., 2004).

After careful consideration, we decide to head towards the use of a unimodal tactile system for navigation tasks. In addition to the fact that it was an unexplored research space, we have earlier listed benefits of tactile navigation systems (Section 1.1.3). In the next subsections, we describe related work that deployed tactile cues for navigation purposes, research projects that tested its effect on different body sites, and representation techniques used for spatial information.

Tactile cues for direction and spatial orientation

Research has investigated on the effect of tactile cues for direction and spatial orientation. Results have demonstrated that they enable hand-free and eye-free movement and thus allow attentional resources for other important tasks both in lab-based studies and in a real-world environment (e.g. in Elliott et al., 2006; Elliott et al., 2010). In particular, they allow faster reaction times, better awareness of the situation, and stable orientation (Elliott et al., 2009).

Direction cues can be a simple vibration pattern manipulating signal frequency and duration, composed of two tactors (Dobbins & Samways, 2002; Bosman et al., 2003), but are more often composed of 8-12 tactors arranged in a linear fashion around the body, i.e. belt (e.g. Tsukada & Yasumura, 2004), or an array pattern, i.e. a 3x3 array on a vest (e.g. Ross & Blasch, 2000). The cues have been demonstrated to help aid navigation in virtual

[21] Modality fission refers to the process of splitting semantic meaning from a modality-free into different modality streams for presenting back to users via appropriate output channels.

environments (Lindeman et al., 2005; Ghosh et al., 1998), bicycle (Poppinga et al., 2009), cars (Ho et al., 2007; Scott & Gray, 2008; Van Erp & Van Veen, 2004), aircraft (Cholewiak & McGrath, 2006; Chiasson et a., 2002), indoor navigation (Bosman et al., 2003), land navigation (Van Erp, 2005; Nagel et al., 2005; Elliott et al., 2007; Frey, 2007; Pielot & Boll, 2010) and navigation for visually impaired users (Ghiani et al., 2008; Gustafson-Pearce et al., 2005; Amemiya et al., 2004; Marston et al., 2006; Amemiya & Sugiyama, 2008).

Spatial orientation cues are similar to direction cues but are based on a specific purpose of providing positional and loci orientation, e.g. in an easily disorienting environment such as in an aircraft or a helicopter (Elliott et al., 2009). Results have shown tactile cues' effectiveness in guiding pilots for landing and hovering tasks (e.g. Van Erp, 2005; Van Erp et al., 2003)

Body sites and wearable device layouts

Table 2.2 Tactile Wearable Interfaces for Navigation Classified by Their Body Contact Areas and Forms

Body contact areas	Forms	Products or Research Projects
Head	Headband	Forehead Retina System (Kajimoto et al., 2006), Haptic Radar (Cassinelli et al., 2006)
Shoulders	Shoulder Pad	Active Shoulder Pad (Toney et al., 2003)
Back Torso	Vest	Tactile Land Navigation (Duistermaat, 2005)
Back Torso	Chair	Haptic Back Display (Tan et al., 2003)
Back Torso	Backpack	3x3 Tapping Interface Grid (Ross et al., 2000), Personal Guidance System (Loomis et al., 2001)
Around the waist	Belt	ActiveBelt (Tsukada et al., 2004), WaistBelt (Van Erp, 2002) (Van Erp et al., 2005) (Ho et al., 2005), Tactile Wayfinder (Heuten et al., 2008)
Wrist	Wristband	GentleGuide (Bosman et al., 2003), Personal Guide System (Marston et al., 2007)
Fingers	Wristwatch with Finger-Braille Interface	Virtual Leading Blocks (Amemiya et al., 2004)
Feet	Shoes	CabBoots (Frey, 2007)

Table 2.2 summarises various forms of tactile wearable interfaces, which convey directional information on different body sites. Some of these systems (e.g. Ross et al.,

2000; Frey, 2007; Van Erp, 2002) have been tested in both virtual and operational environments and were reported to be successful.

Since several tactile-based directional displays have already been proposed and successfully tested, we were interested in finding the most effective of these approaches.

Representation of spatial information

In this section, we review techniques used to represent spatial information seen in the abovementioned systems. There are two main approaches to creating informative tactile stimuli: the abstract and symbolic approaches (MacLean, 2008b). Abstract representation focuses on manipulating the characteristics of a stimulus, whereas the symbolic approach focuses on the semantic association of stimuli with known metaphors. For example, MacLean & Enriquez[22] (2003) and Brewster & Brown[23] (2004) designed abstract stimuli by systematically varying waveform, amplitude and frequency of vibration signals, while Chan et al. (2005) designed a symbolic tactile set in which signal patterns were associated with heartbeat and finger-tapping metaphors. We have found that much tactile spatial representation research using either technique focuses on two information categories: direction and distance.

Previous research in tactile navigation (e.g.Tan et al., 2003; Van Erp et al., 2005; Raisamo & Myllymaa, 2010) proposed symbolic mapping for the representation of directional information, involving the mapping of a limited set of cardinal and ordinal directions (i.e. allocentric) to their associated vibration signals. These signals have commonly been generated using one of two techniques: (1) simulation of straight-line patterns (i.e. pointing arrows) on an array of actuators, e.g. Tan et al., 2003 and Raisamo & Myllymaa, 2010; and (2) an absolute point vibration for each direction in a distributed placement of actuators around the waist, e.g. Van Erp et al., 2005. Representing direction using an abstract approach may be useful if the sizes of the body contact area or devices are limited (e.g. see an example in MacLean & Enriquez, 2003).

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[22] The abstract tactile patterns known as Hapticons (see Glossary for explanation).

[23] The abstract tactile patterns known as Tactons (see Glossary for explanation).

A representation of distance was studied using both abstract and symbolic approaches. Raisamo & Myllymaa (2010) coded distance information on a back array with symbolic metaphor by generating a cutaneous sensation of an “up” or “forward” line (i.e. buzzing from bottom to top actuators in a sequential manner) when a user is closer to a destination. On the other hand, Pielot et al. (2010c) have experimented encoding distance on a belt wearable device using an abstract approach by manipulating three signals’ attributes: duration, rhythm and intensity. Results for the best attribute were inconclusive. Researchers concluded that the duration-based technique was the most difficult to interpret. Van Veen et al. (2004) also used an abstract approach to code distance by manipulating signal rhythm (i.e. by increasing or decreasing interstimulus gap duration), generating a different level of “close” illusion when a user moved closer to a target. Different from Pielot et al. (2010c), Van Veen et al. (2004) found that participants were able to interpret several distance coding techniques with no difficulty.

Previous work cataloged in this section has shown that tactile interaction can be represented and understood by users and yield positive results. The next section discusses how the research topic could be explored and extended.

2.4 Resolving issues in tactile pedestrian navigation research

In Sections 2.1-2.3, we have described relevant literature including pedestrian navigation in urban environments and, role of technologies in navigation and related work in tactile navigation. In this section, we will define the needs to improve tactile navigation systems.

As the tactile research has advanced, its potential benefits have grown beyond the initial suggestion that it can be used to substitute visual sensory for simple shape projection and braille learning (Duistermaat, 2005; Tan & Pentland, 2005). Some research has already shown that tactile interaction can enrich our daily and recreation activities such as navigation (Ross & Blasch, 2000), dance training (Gentry & Murray-Smith, 2003) and alpine touring (Rehrl et al., 2010). Although we have seen quite a rich list of literature involving the use of tactile channels to deliver useful information for a variety of tasks, tactile research in the navigation domain is still in its initial states. There are several issues in relation to practical use that remain to be investigated. These consist of the *design* and *usability* issues such as how to represent different levels of spatial granularity and how much spatial information we can transmit down the tactile channel as well as the effect of a unimodal tactile navigation system and its acceptance. We need to further investigate and understand this less-studied sensory channel to benefit from its richness and flexibility.

As for tactile representation techniques, although proposed, they have not been fully investigated and compared. Hence, careful design of tactile signal patterns is crucial to its effectiveness because we have learnt that touch is a private event and it is momentary (Schiffman, 1976). Our research would investigate on how to properly design vibrotactile signals for spatial information in which individuals could perceive, distinguish, interpret and use them for navigational decisions. Specifically, we aimed to examine these representation techniques for different types of spatial information including the effect of their combination.

Prior to execution, it was necessary that we sought a clear definition of related concepts because this could help us identify factors affecting navigators' cognitive process and behavior, thereby designing better experiments (Carroll, 2003); as well as understand how the touch sense works and what vibrotactile signal attributes are because these would enable us to associate physical stimulation parameters with well-defined percepts (Tan & Pentland, 2005).

In the following subsections, we will first elaborate the basis of the research program (Section 2.4.1). Then, we carefully examine the issues required to be investigated for the design and development of tactile navigation displays. They are classified into two categories: design (Section 2.4.2) and usability (Section 2.4.3) issues.

2.4.1 The basis for the research program

This subsection covers four topics including related theories and design guidelines, psychophysics of touch in relation to navigation tasks, factors affecting touch perception, and vibration tactile attributes.

Related theories

Theories and guidelines reviewed in this subsection helped describe phenomena, explain processes, predict outcomes, and support recommendations in relation to the design of tactile-based assistive systems. They provided the foundation of our research program. In particular, these include MRT, Prenav, Choreme and several guidelines as follows.

Multiple resources theory (MRT)

Wickens' Multiple Resource Theory (1980, 1984, 1992, 2002) focuses on aspects of workload and conflicts in information processing (Elliott et al., 2009). MRT can be summarised as follows (Elliott et al., 2009):

- Humans have several semi-independent cognitive resources
- Some resources can be used near-simultaneously without impairment to performance while others cannot
- Tasks requiring the use of different resources can be effectively performed together
- Competition for the same resource can produce interference
- Dissimilar cognitive resources exist to process information from different sensory channels (e.g. visual, audio or touch information).

In general, the theory predicts the human operator's ability to perform in high-workload, multi-task environments by viewing processing as constrained by several pools (e.g. sensory systems) of limited resources. Level of interference between two tasks that require the same modality's attention is usually higher than that between two cross-modal tasks (MacLean, 2008b). Wickens (1980, 2002) also suggested that presenting information through an idle sense would not increase overall cognitive load.

Prenav

Prenav[24] is an integrated model of human navigation and workload proposed by Van Erp (2003). Unlike MRT, Prenav emphasises performance that can be automated. The model demonstrates a level at which some tasks can be performed automatically without involving cognition (Van Erp et al., 2006). This could be achieved with regard to the long-term effect, e.g. years of practice, automaticity and intuitive response (Elliott et al., 2009). It consists of two loops: the information processing and the workload loops. The information processing loop contains four circulated processes: sensation -> perception -> decision -> action and back to the sensation process via environment or display (see Figure 2.5). The workload loop describes the state of the operator on the information processing loop. It is suggested that external stressors such as sleep deprivation and vibration may affect the state of the operator (Van Erp et al., 2006).

The Prenav model explains how tactile cues affect attention, cognition and performance that are highly intuitive and associated with the fastest reaction time compared to other modalities' cues.

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[24] It combines Sheridan's (1992) model for supervisory vehicle control, Wickens' (1984, 1992) information processing model, Veltman and Jansen's (2004) workload framework and Rasmussen's (1982, 1983) framework of skill-based, rule-based and knowledge-based behavior.

Elliott et al. (2010) proved that Prenav and MRT are correct. The studies compared the visual and tactile navigation systems' performance under workload situations at night time. Both the Prenav model and MRT predict that an intuitive display is more effective in high workload situations than a non-intuitive display and that there are performance advantages if information is being represented via a less taxed channel (i.e. At night, the taxed channel is the visual one. Hence, presenting information via touch is beneficial.).

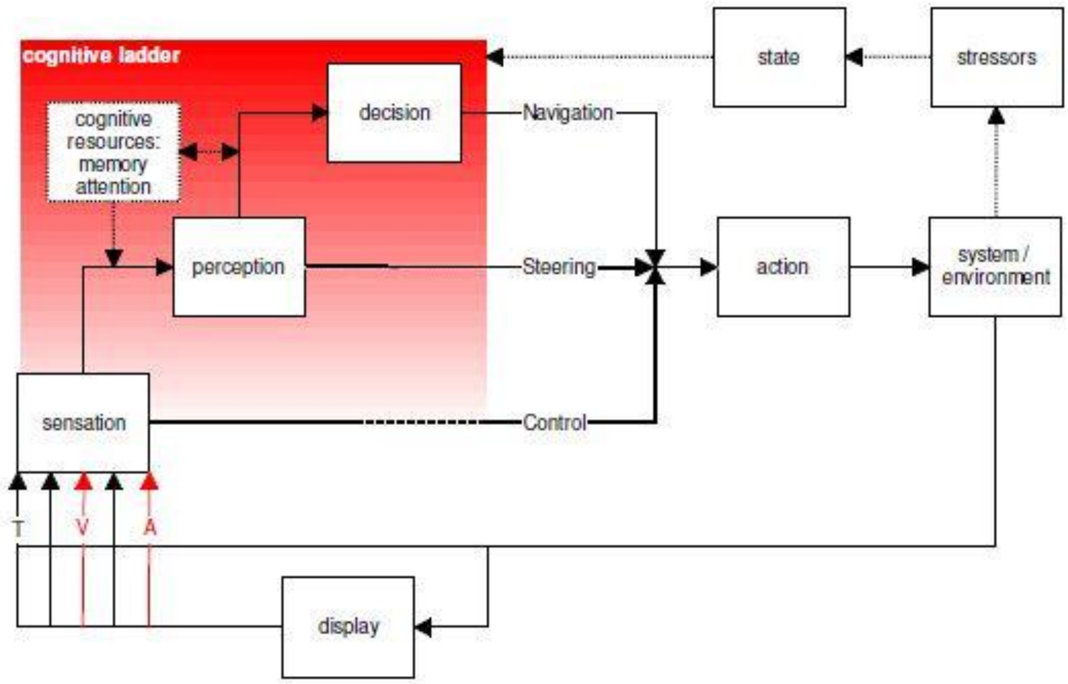

Figure 2.5 Prenav model (Source: Van Erp, 2007)

Choremes theory and Qualitative spatial action model (QSAM)

Choremes theory (Klippel, 2003; Klippel et al., 2005) is defined as a limited set of mental conceptualisations of primitive functional wayfinding and route direction elements. The wayfinding Choreme theory follows QSAM (Hernandez, 1994; Cohn & Hazarika, 2001).

QSAM is a sequence of abstract spatial actions. Specifically, it combines landmarks and passages with the representation of orientations (e.g, turn left or right), spatial relations (e.g., on the left or right) and motion actions (e.g. walk, climb, cross, downhill, follow, pass, turn). QSAM's conceptual user model provides an abstract topological representation of navigation with well-defined spatial relations (Shi et al., 2007). Figure 2.6 demonstrates such a topology. There are six areas, seven on the lines, and two points. Moreover, the concepts with respect to route segments, i.e., *entry*, *exit* and *course*, are used to represent some positions, like *atEntry*, *onCourse*, *rightAtEntry*.

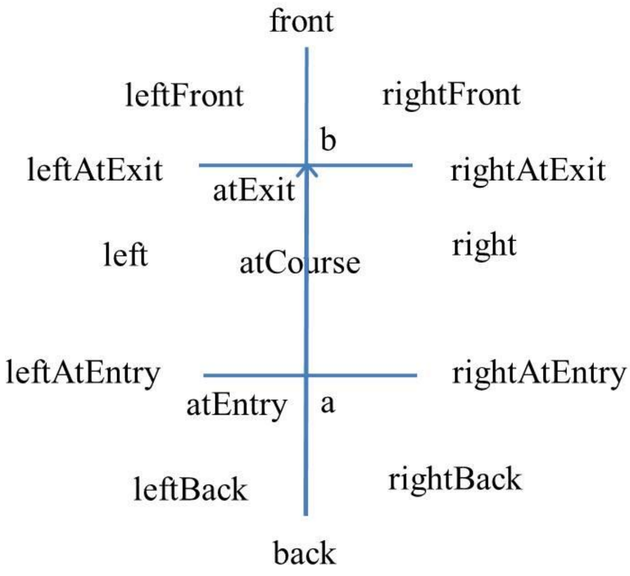

Figure 2.6 QSAM's orientation grids with 15 different positions (Source: Shi et al., 2007)

Instead of modeling path networks, Choremes characterise routes based on concepts of turning actions at decision points. In the eight-direction model (see Figure 2.7), each sector represents 45 degree increments for each direction. Choremes conceptualise a person's position on one route segment (the one that the navigator is on – see the right picture in Figure 2.7), leaving seven other possible directions to turn (see Figure 2.8). *Back* is considered a special concept and has not been explicitly included in the model.

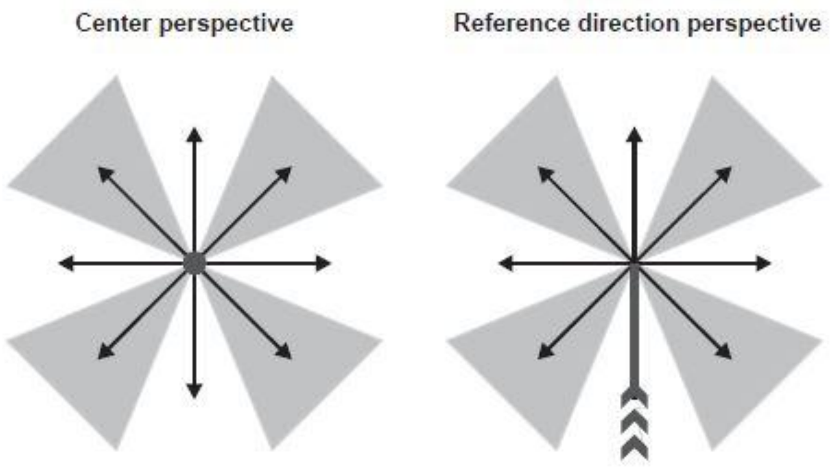

Figure 2.7 Choremes' eight direction model (left picture) and seven potential turns (right picture) for a route direction context (Source: Klippel et al., 2005)

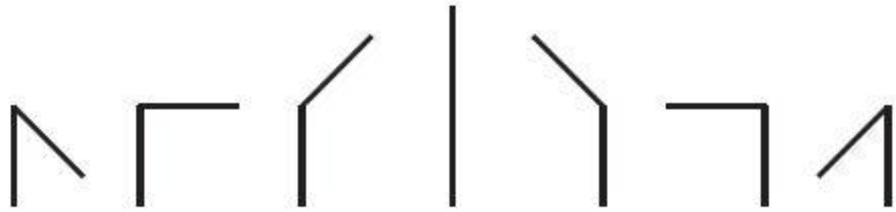

Figure 2.8 The seven wayfinding choremes' graphical externalisation. Their linguistic externalisation is known as sharp right, right, half right, straight, half left, left and sharp left accordingly.

The combination of both Choremes and QSAM will be used as a basis for the design of our empirical studies' conceptual design. We have learned that directions can be classified as intrinsic (proposed within Choremes, e.g. veer left, sharp right) and extrinsic (proposed within QSAM, e.g. cross along, down to, out of, up to) concepts. The *QSAM*'s *turn and motion actions* and *Choremes' primitive functions* allow us to classify navigation activities according to actual environments (cf. allocentric directions). For example, turns can be either intrinsic (e.g. turn right) or extrinsic (e.g. turn in the direction of the bridge). Similarly, motions can be intrinsic (e.g. walk straight) or extrinsic (e.g. walk towards the church).

Useful guidelines for the design of tactile navigation systems

A number of studies have proposed guidelines for the design of tactile navigation systems. This thesis has taken the following suggestions into account for our empirical studies' design and execution.

Research has indicated that users would like hand-free and eyes-free solutions to navigation tasks (Magnusson et al., 2009). This can be best achieved by using the users' torso as the display location (Subramanian et al., 2005). Researchers recommended that the system should provide essential spatial information, e.g. confirmation cues, as well as additional functions, e.g. correcting user's orientation (Magnusson et al., 2009). However, an amount of information provided by the system should be kept to minimum (Kwok, 2005). These suggestions directly support our proposal to investigate the use of a wearable device for wayfinding tasks. We expected to provide compelling evidence that the use of tactile feedback has the potential to reduce the number of navigation errors and decrease navigation completion times (Carter & Fourney, 2005; Oakley et al., 2002).

For the design of tactile patterns, we incorporated suggestions from several guidelines (Jones & Sarter, 2008; Brewster & Brown, 2004; Van Erp, 2002; Van Erp, 2005b; Subramanian et al., 2005; Ternes & MacLean, 2008; Hale & Stanney, 2004; Nesbitt, 2005b). Specifically, we would describe a list of vibrotactile signal attributes (Jones & Sarter, 2008), which we aimed to manipulate in our experiments, and their implications for design (e.g. Brewster & Brown, 2004; Jones & Sarter, 2008; Van Erp, 2002; Van Erp, 2005b) in the later subsection on *Vibrotactile signal attributes*. We also followed Hale & Stanney's (2004) suggestions that the design of tactile feedback must consider psychophysical aspects of touch; this topic was explored in the next subsection on *Psychophysics of touch.*

Previous research has reported that users can be trained to recognise abstract tactile representations (Subramanian et al., 2005); this has led us to explore several abstract techniques for landmark representation such as coding tactile information by location (Van Erp, 2002) and by temporal patterns (Ternes & MacLean, 2008) (see Section 5.3.2).

These presented guidelines summarise accumulate knowledge in the tactile research domain and encourage reuse of good design solutions (Nesbitt, 2005b). Our plan was to extend them by systematically manipulating and measuring the effect of different designs of tactile signals for spatial data.

Psychophysics of touch in relation to navigation tasks

One cannot design proper interaction to suit human needs without understanding people and their capabilities. To clarify the focus of the thesis, we would like to clarify a distinction between active (manipulation) and passive (sensing) touch. Active touch is known as *haptic manipulation* whilst passive touch can be either *tactile* (cutaneous) or *kinestheic* sensing. Active touch involves *active stimulus exploration* and *voluntary body movements*[25] whilst passive touch lacks these qualities and involves only the excitation of receptors in the skin and its underlying tissue (Gibson, 1962). The focus of this thesis will be on tactile perception. Specifically, we focus on the tactile sensing (i.e. mechanical pressure on skin) by providing a vibrotactile signal.

In this subsection, the core aspects, both psychological and physiological, of touch are examined including tactile perception, sensitivity and tactile memory.

[25] See Glossary.

Tactile perception

Perception is the process by which we receive and interpret information from the world around us via different sensory organs and transform into experiences of objects, events, sounds and tastes (Schiffman, 1976; Sharp et al., 2007).

Tactile perception[26] is the sense of pressure perception, generally on the skin, the largest organ of the body[27]. There are a variety of pressure receptors that respond to variations in pressure (e.g. firm, brushing, sustained etc.). Stimuli are detected through a large number of nerve endings and different types of sensory receptors (see Table 2.3) under the skin before being sent through sensory pathways leading towards the central nervous system in the brain for recognition and discrimination processes (Kostopoulos et al., 2007). Perception of the touch sense depends on the type of receptors that are sensitive to different kinds of stimulation on the skin.

Table 2.3 Mechanical sensory receptors (Adaptation from Aragon, 2006; Myles & Binseel, 2007; and Hsiao et al., 2003)

	Sensory receptors	**Function**
Tactile – see Figure 2.9 for reference	Mechanoreceptor :	Detect skin deformation
	(a) Merkel disks	Temporal sensitivity 0.4-100 Hz Small receptive field Sensing skin curvature, local shape, roughness and pressure
	(b) Meissner corpuscles	Temporal sensitivity 10-100 Hz Small receptive field Respond best to active touch involved object exploration (Sensing surface curvature, velocity, local shape, and grip control)
	(c) Ruffini endings	Temporal sensitivity 15-400 Hz Larger receptive field Sensing skin stretch and lateral force
	(d) Pacinian corpuscles	Temporal sensitivity 40-700 Hz Extremely sensitive over a large receptive field Sensing vibration, slip and acceleration

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26 See Glossary.

27 For example, an average 6 feet tall man has about 3000 $inches^2$ of skin area (Schiffman, 1976).

Touch sensitivity

Regions of the skin are not uniformly sensitive to all stimuli (Schiffman, 1976). For each area on the body, the sensitivity level is different depending on the size of the receptive field (i.e. the density of receptors). If there is a high density of receptors, it is likely that effective resolution is reduced. Exploratory parts of the body (i.e. fingers, nose, mouth and tongue) are highly sensitive areas while legs, arms and trunk are much less sensitive. Figure 2.10 demonstrates examples of different sizes of receptive fields on a thumb and a wrist.

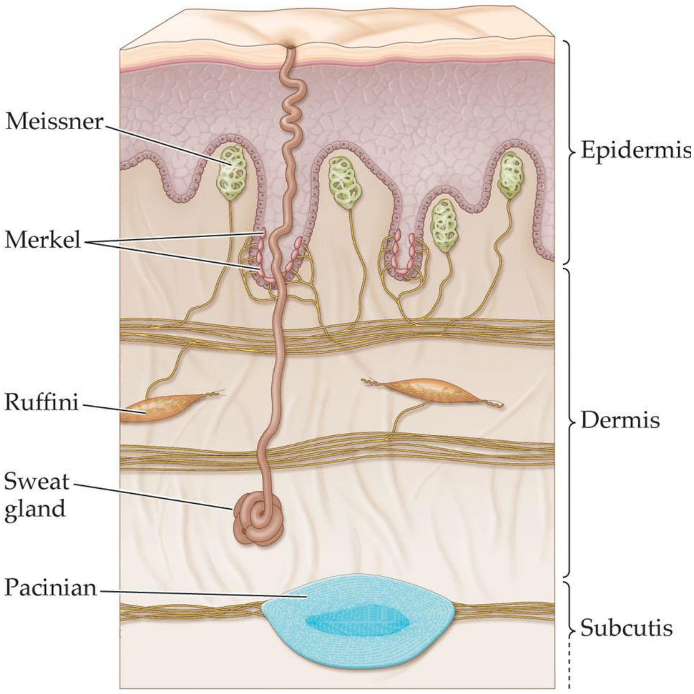

Figure 2.9 Cross-section of the skin (Source: Aragon, 2006)

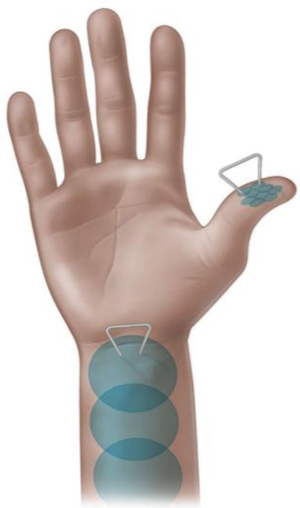

Figure 2.10 Receptive fields on wrist and hand

Spatial resolving capacity (Two-point thresholds)

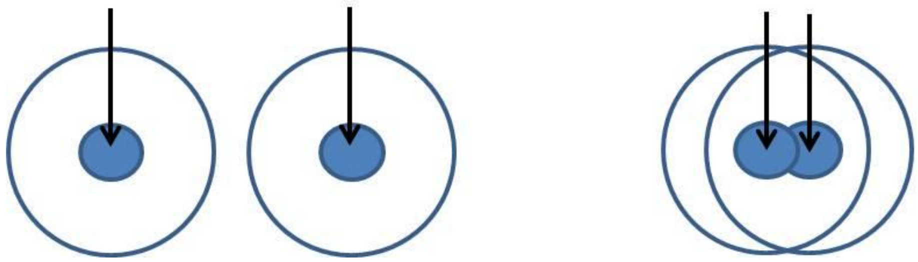

Figure 2.11 Two-point threshold (Source: Aragon, 2006)

The least distance between the two stimuli that is perceived as two distinct stimuli is known as a two-point threshold (Schiffman, 1976). If a single region of the skin surface is stimulated by two stimuli, it could feel like a unitary sensation given that the two points are too close. This situation can be avoided if there is a separation in distance between the two points (see Figure 2.11). These two-point threshold values vary with different parts of the body; the more mobile the area stimulated, the lower the two-point threshold (Schiffman, 1976). For example, the two-point threshold values are 2-3 mm for fingers and 3.5-4 cm for around the waist and back areas. For the full list of two-point threshold values, see Weinstein, 1968 (p.202) or Schiffman, 1976 (p.101).

Sensory adaptation

An area on the body which is stimulated for a lengthy period of time may experience sensory adaptation (Schiffman, 1976). It is characterised by a decrease or even a complete elimination of a signal's perceived intensity (Myles & Binseel, 2007). Kaczmarek and Bach-y-Rita (1995) reported that the adaptation rate varies with frequency; little adaptation occurs with a 10Hz vibrotactile stimulus, while the skin adapts very quickly to a 1000Hz signal. It can be avoided by: providing a brief movement of the stimulus (Schiffman, 1976), providing a form of abrupt change in the stimulation (Schiffman, 1976), and giving a signal with shorter length (Myles & Binseel, 2007).

Memory vs Tactile memory

Memory is the capacity to remember and involves recalling various kinds of knowledge that allow us to act appropriately (Eysenck & Keane, 2005). It is usually divided into a set of memory processes and a number of different types of memory stores. The processes of remembering include storing information in memory and then retrieving it later by way of recall and/or recognition processes. Memory stores can be divided into two types: short term or working memory; and long term memory. Short-term storage is a system of high capacity but short duration (Gallace & Spence, 2009). As a result, if any information is located in this part, it is likely to fade quickly. Tactile memory is based on the same cognitive mechanism of storing and retrieving tactile information, for example to recognise sensations that have previously been explored.

Spatial numerosity judgments

Tactile numerosity judgments refer to the measurement of our spatially tactile span of consciousness (i.e. maximum threshold) of a number of stimuli *simultaneously* presented at any one time across the body. This ability is sometimes being referred as subitising (Gallace & Spence, 2008).

Researchers (Riggs et al., 2006; Bliss et al., 1966; Gallace et al., 2008) reported that humans were able to subitise up to three locations of simultaneously presented tactile signals across the body, subjected to signal's intensity (i.e. the stronger, the better the detection performance).

We should note here that the threshold of three in tactile numerosity judgments is similar to that of visual (2-3) and audio (2-3) judgments (Gallace & Spence, 2009).

Temporal numerosity judgments

Temporal numerosity judgments refer to the ability to distinguish stimuli presented *sequentially* on one location or across body sites. It is reported that the maximum interstimulus interval between two stimuli is around 40-60 ms for the stimuli to be perceived as simultaneous (Gallace & Spence, 2008).

Memory decay

There are a few factors affecting how quick tactile memory decays. These factors were reported to include:

- The gap between the moment being stimulated and the recall event – the wider the gap, the more it fades (Gilson & Baddeley, 1969; Miles & Brothwick, 1996)

- The sensitivity of the skin site – the less sensitive area, the higher the degree of forgetting rate (Murray et al., 1975)

- A number of stimuli being presented simultaneously – the greater the number, the faster the decay (e.g. if there are less than five simultaneous stimuli, tactile memory could last 5000 ms, otherwise it lasts only 1000 ms) (Gallace et al., 2008)

- Articulatory suppression and crossmodal masking (see Gescheider & Niblette, 1967; and the later subsection *Effects from other modalities*)

Implications for design

We must note here that all information presented in this *Psychophysics of touch* subsection came from studies as early as in the 1960s and focused on the finding of threshold values with static touch. We are aware that all the values may deviate when it comes to vibrotactile stimulation. However, understanding psychophysics of touch allows us to appropriately design the system and stimuli that are compatible with human's physical capabilities and limitations. For example, if we are to use vibrotactile stimuli for tactile communication, we need to make sure that the signal stimulates the Pacinian corpuscles (see Table 2.3 and Figure 2.9) by providing vibration at frequency range of 40 – 700 Hz.

We have learned from previous research that we should present 1-2 stimuli at any one time in a tactile display. The number may go up to three if the vibration is presented on the area where there are a high number of sensory receptors. If we are to present sequential stimuli that are supposed to be perceived as separate ones, the interstimulus duration must exceed 60 ms.

We also see in this subsection's explanation that tactile memory decays very quickly. As a result, tactile feedback design should allow users to recognise the meaning of sensation rather than having them to be recalled from the users' memory (Sharp et al., 2007; 2011).

Factors affecting touch perception for navigation tasks

Perception in real environments is influenced by various factors such as light & noise in the environment and users' anxiety and fatigue (Révész, 1950; Sharp et al., 2011). In addition, other factors include the effect from: (1) individual differences in terms of age, gender & navigation experience, (2) individual differences in spatial abilities and (3) other modalities.

Individual differences in terms of age, gender and navigation experience

For age difference, researchers (e.g. Verrillo, 1993; Klatzky & Lederman, 2002; Kaczmarek & Bach-y-Rita, 1995) have addressed that age has a significant effect on cutaneous thresholds due to the loss of a number of mechanoreceptors. As a result, deterioration of tactile perception occurs in the older population.

As for gender difference in relation to navigation tasks, it is confirmed that there are differences between males and females in navigation behavior and ability (Burnett, 1998). Males seem to have stronger orientation skills than females and feel little or no anxiety during the course of navigation (Mashimo et al., 1993; Millonig & Schechtner, 2008). Ward et al. (1986) revealed that males used cardinal directions (e.g. North, South) and distances whilst females relied on landmarks and relational directions (e.g. left, right).

As for the difference in terms of navigation experience, there are factors such as experience in land navigation, especially in unfamiliar areas, assistive technologies and navigation techniques used. For the navigation experience effect, Gould (1989) noted that experienced travellers possess a higher level of navigation skills than rare travellers.

Please note that, to date, there is no empirical study to have directly indicated the implications of aging, gender and navigation experience for tactile pedestrian navigation.

Individual difference in spatial abilities

Individual differences in spatial abilities, identified by a few researchers (e.g. Michael et al., 1957; McGee, 1979) composed of separated abilities, mainly refer to three things: (1) spatial visualisation, (2) spatial relations and orientation, and (3) kinesthetic imagery. Carroll (1993) broadened the definition of spatial abilities to also include: (4) closure speed, (5) flexibility of closure, (6) perceptual speed and (7) visual memory.

Spatial visualisation is thought to require mental manipulation of objects (ability to manipulate, rotate, twist or invert objects without reference to one's self). *Spatial relations and orientation* involve the ability to understand the arrangement of elements within a visual stimulus. *Kinesthetic imagery* associates with left-right discrimination. *Closure speed* and *flexibility of closure* both involve the ability to identify a stimulus or part of a stimulus that is either embedded in or obscured by visual noise. *Closure speed* involves the ability to access representations quickly from long-term memory. *Flexibility of closure* associates with the ability to hold a stimulus in working memory while attempting to identify it from a complex pattern. *Perceptual speed* is speed in comparing figures or symbols, scanning to find figures or symbols, or carrying out other very simple tasks involving visual perception. *Visual memory* is the ability to remember the configuration, location and orientation of figural material. In general, the difference in high and low-spatial individuals concerns the quality of the spatial representations that they construct and their ability to maintain this quality after transforming the representations in different ways.

Researchers (i.e. Goldin & Thorndyke, 1983; Streeter & Vitello, 1986) found that people with good navigation skills excelled at reading cues on the map, learning an environment from navigation or from a map, and at manipulating spatial information in memory. Streeter & Vitello (1986) also noted that people with poor spatial skills have a greater need for reassurance and mainly relied on landmarks during the course of navigation.

Effects from other modalities

It has been reported that information from different sensory channels can affect the awareness (Gallace & Spence, 2008) and performance (Klatzky & Lederman, 2005) of a signal presented in another sensory modality. Effects can yield both positive and negative results.

Turchet et al. (2010) created a simulation of audio and haptic sensation of walking on different surfaces (i.e. wood, snow, gravel, and metal). The system provided both coherent and incoherent audio-haptic stimuli for those surfaces. Results showed that using coherent information across two modalities results in sensory augmentation. Papetti et al. (2010) created an audio-tactile system that provides the sensation of walking over grounds of different types (granular or crumpling properties) which enhances the user's walking experience. However, if they were incoherent, the auditory modality was dominant to the haptic one (i.e. participants chose answers based on audio stimuli).

Implications for design

Realising these factors could help us carefully design empirical studies such that we could avoid impotent results. For example, the design of vibration patterns must not conflict with the sound produced or the vision displayed.

Vibrotactile signal attributes

The thesis would employ vibrotactile stimuli because they were considered safe[28] and required low power consumption (Tan & Pentland, 2005). Vibrotactile[29] signals are

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[28] We did not consider different types of sensation such as electrical or electro-mechanical at all because of their tendency to induce pain and discomfort (Tan & Pentland, 2005).

[29] Besides vibrotactile sensation, there is another type of tactile stimulation called electrotactile signals. Electrotactile sensation is provided by stimulators generating direct electrical stimulation of the nerve ending on the skin.

vibration patterns generated by stimulators providing pressure through the properties of the mechanoreceptors of the skin. The dynamic response of tactile nerve endings in the skin to these vibration signals is known as vibrotaction. Vibrotactile experiences are formed by repeatedly stimulating parts of the body at a set of contact points. Stimulators can be motors or vibrators on their own or be formed as an array or of specific layouts to deliver more sophisticated shapes and patterns.

As vibrotactile patterns are aimed to stimulate mechanoreceptors to achieve intended vibrotaction experience, a few attributes of vibrotactile signals are required to be understood and carefully considered when designing tactile communication systems. These attributes include: frequency, duration, rhythm, size of body contact areas and location on the body (Jones & Sarter, 2008).

Frequency of signal

Frequency is the measurement of the number of occurrences of a repeated event per unit of time, or the rate of change of phase of a waveform, measured in Hertz (Hz) – how many times an event repeats per second. Frequency is sometimes measured as revolutions per minute (rpm) – the number of full rotations completed in one minute around a fixed axis. For example, r/min = (1/60) revolutions per second = 0.01666667 Hz (see example in Figure 2.12).

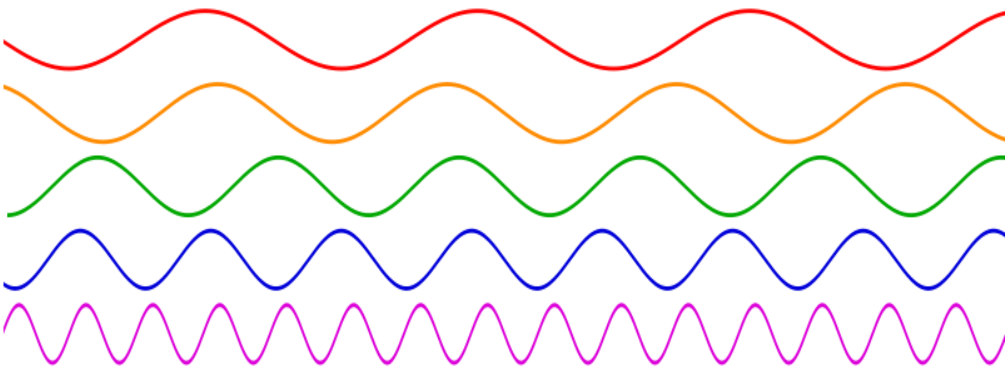

Figure 2.12 An example of different frequencies of sine waveforms, the bottom line is of the highest frequency. (Source: Google)

Temporal attributes of signal

For the time variable of the signals, there are three temporal attributes: the burst duration of the stimulus, the pulse repetition and the number of pulses. The burst duration refers to the period of time during which a vibration continues.

Signal rhythm

Signal rhythm is defined as a movement marked by the regulated succession of weak or strong elements of signals by manipulating a signal's frequency, amplitude and duration—or a combination of them.

The size of body contact areas

This refers to the dimension of skin contact points or locations on the body. The size of body contact areas can be increased by two manners: (1) increasing the dimension of a single contact location and (2) increasing the number of contact points on the body.

Location on the body

We can provide vibrotactile signals to any area on the body. However, some areas are too sensitive for some people that they experience a tickling effect when stimulated by vibrotactile feedback. The torso area is the most popular location advised by researchers (e.g. Raisamo & Myllymaa, 2010; Hoggan & Brewster, 2006a; Myles & Binseel, 2007).

Implications for design

Manipulation of the abovementioned properties provides different tactile sensations (Brewster & Brown, 2004). This dissertation focuses on vibrotactile feedback to allow a sense of vibrating objects. Specifically, in our study such objects are disk motors (which will be called actuators interchangeably). Mechanical vibration in motors is considered a kind of wave, which has a square shape. Physical characteristics of vibration to be modeled are frequency and duration of vibration signals as well as their manipulation to achieve a variety of rhythms. In any instance that these attributes are to be presented at the same time, the number of level values of each attribute should be between 2-4 levels (Brown et al., 2006b).

It is advisable that we follow the level of thresholds suggested when it comes to testing frequency of signals. For frequency threshold, researchers suggested generating vibration at 150-300 Hz (Van Erp, 2002; Van Erp, 2005b; Jones & Sarter, 2008).

Please note that we did not seek to manipulate signals' amplitude in this thesis following Hoggan & Brewster's (2007) report on its inefficiency compared to signals' frequency.

We also realise that the tactile perception is adapted through time and could lead to fatigue. However, Van Erp (2005b) noticed that timing acuity can have both a positive and negative effect. The preferred choice in the trade-off between speed of presentation (dependent on timing parameters) and the spatial resolution may be dependent on the application. He suggested that those applications requiring a high spatial resolution (i.e. localisation-ability to identify stimulated location) benefit from longer presentation times, whilst those requiring a short presentation may require a larger distance between actuators (Van Erp, 2005b). Jones & Sarter (2008) suggested the optimal burst duration from 80 – 500 ms when 50 – 200 ms is appropriate as an alert signal.

All of the above information will be taken into account when we design signals and the actuator's spatial resolution.

Choosing an appropriate site on the body is crucial to tactile perception in relation to the task (Ternes & MacLean, 2008). MacLean & Hayward (2008) advised that the location should not be on finger tips because they might be engaging with other tasks. Furthermore, given its tiny size, a finger can perceive only three intrinsic directions: left, right and backward (Lylykangas et al., 2009). The more suitable sites include chest, waist and back. Hoggan & Brewster (2006a) reported that the waist area is the most distinguishable body site compared to wrist and ankle when it comes to walking. This suggestion is backed by Myles & Binseel's (2007) advice that users were more comfortable with stimulation on the torso area.

Humans' tactile capabilities must be taken into account when designing signals. According to the European standard on haptic perception, people can perceive up to 15 different intensity and nine frequency levels. However, it is doubtful that in operational environments, where users' attention is engaged with other important tasks, users can perform up to such a high standard. In the absence of workload, it is reported users can learn seven signals with little training. However with the presence of workload, it will take users 25 minutes to learn 7-9 signals (Myles & Binseel, 2008). Researchers concluded that the more workload, the longer detection time required.

Currently, there is no reported evidence on the optimum combination of these properties. Our thesis is set to trial and find a set of distinguishable and perceptible tactile signals that can be used to represent spatial information.

Now that we have gathered all essential sources of clarification, next we discuss how we propose to investigate both design (Section 2.4.2) and usability (Section 2.4.3) issues regarding the design of tactile navigation displays guided by the abovementioned foundations.

2.4.2 Design issues in tactile research for pedestrian navigation

The tasks

This study of tactile representation for spatial information has a concern about the kinds of tasks to be represented. It has been reported that different kinds of tasks require different levels of representation (Gallace & Spence, 2008). We have to make sure that the representation we use is suitable for explicit tasks such as identification and categorisation of spatial information rather than a representation for more implicit tasks such as forced choice selecting or same/different judgment (Ladavas et al., 1997). Before we can list what spatial information should be provided to pedestrians in our navigation systems, we should start with the list of tasks during users' navigation process.

According to the navigation models listed in Section 2.2.1, at this stage, we may assume that pedestrians require *previewing* routes, *identifying* directions (to take), *identifying/classifying* landmarks (as points of references and interest), *confirming* if they are on the right path, *orienting* themselves and *controlling* their movements towards intended directions and destination(s). However, as we have learned that tactile communication lacks the ability to provide overview information, we will exclude this task from our consideration. The controlling movement task will also be excluded because it is a person's motor control ability and is beyond the scope of our study.

Next, we will identify the types of spatial information that should be provided by our tactile navigation system for each task. This is our attempt to answer our first RQ.

> ***RQ1: What information types should the tactile navigation display provide to pedestrians?***

Information to be represented

Based on the list of tasks in the previous subsection, we can primarily conclude that spatial information types that will accommodate these tasks are direction (for identifying), landmark (for identifying and classifying) as well as cues for confirming and orienting tasks.

Our list is congruent with those suggestions provided by other researchers (e.g. May et al., 2003; Bradley & Dunlop, 2005; Magnusson et al., 2009; Ross et al., 2004; Pielot & Boll, 2010). Ross et al. (2004) and Pielot & Boll (2010) have identified landmarks as the most important spatial information required for pedestrian navigation because they help increase users' confidence and performance and build survey knowledge. In some situations, Pielot & Boll (2010) noted that users did not require turn-by-turn information as long as they could visualise upcoming landmarks. However, we insist that directional information is most crucial to navigation success especially with tactile communication because users will not be able to *see* both direction and landmark cues. We assume that they would require both types of information to aid their navigation.

According to Bradley and Dunlop (2005) the most important information that should be provided in any navigation system was distance. However, May et al. (2003) stated otherwise, that distance was not necessary for pedestrian navigation due to the nature of slow moving speed. In our study, we have decided that distance may not be a good choice to be included because current[30] technology still has flaws in measuring distance. The current technology has a high rate of errors resulting from the rough grained resolution of measurement, the mapping of measurement to distance, obstructions, reflections, and multi-path effects. This makes measuring distance in reality uncertain (get a larger area not a point). However, this requirement can be taken as our future system improvement.

Other types of information suggested by Bradley & Dunlop (2005) such as street name and other types of textual information may not be achievable via tactile communication due to the limitation of tactile signals' characteristics and human perception and cognition capabilities.

In conclusion, we will focus on providing four types of information: direction, landmark, cues for confirmation of one's point on route and information for orientation.

As the Choremes theory and QSAM have identified a limited set of directions required for navigation, we use Choremes' eight direction model as a basis for our signal design of direction, confirmation and orientation cues.

However, landmark is a complex type of information not systematically classified into well-defined categories. Lists of used landmarks in several research papers are subjected to the studied areas, i.e. they were chosen on a case-by-case basis. Several lists of "most used" landmarks have been reported by researchers (e.g. Grabler et al., 2008; Baus et al., 2007). Nevertheless, it is not possible to generalise to a set of landmarks from such single location studies because the landmarks will be highly diverse from one place to another.

[30] Circa 2007-2012.

Burnett (1998) notes the problem for research in this field that only a limited set of landmarks has been drawn from a limited set of evaluated routes.

Sorrow et al. (1999) reported that people use different types of landmarks for different navigation purposes: e.g. visual landmarks are used for navigation to a familiar destination; structural landmarks are used for navigation to an unfamiliar destination; both types are used for exploring the area. There are currently no reported findings on the comparative importance of different landmarks or on their use across different navigation contexts. Hence, there is a need to further investigate the use of landmarks by pedestrians. This leads to RQ2:

RQ2: How do pedestrians use landmarks for different navigation purposes?

We therefore adopted an empirical approach to identifying consistently used landmarks based on people's experiences of journeys involving each of the three navigation purposes (i.e. commute, quest and explore). We carried out the empirical identification and classification of a set of landmarks or landmark types appropriate for the use of mobile navigation systems in urban environments. The classification of landmarks is reported in Chapter 4.

Form of wearable devices and location on the body

Since several tactile-based directional displays have already been proposed and successfully tested, we were interested in finding the most effective form of these layouts. This leads to RQ3.

RQ3: What is the effective form of tactile displays for pedestrian navigation?

We describe our investigation on this issue in Chapter 3. Of the proposed forms (see Table 2.2), we have focused on the wearable systems that use the torso as a display site, specifically belt-type and back torso vest devices. According to researchers (e.g. Tan et al., 2003; Tsukada et al., 2004), their shape, size, and body contact areas support representation of a number of directions and other information. We decided not to consider the headband because it was reported that users had experienced discomfort wearing the system (Myles & Binseel, 2007). For the systems worn on wrists and feet, the size of body contact areas is too small effectively to afford the display of a number of directions (which are required according to the Choreme theory's direction model). We also did not consider the type of systems worn on fingers because users would normally require their hands to be free to perform other activities when interacting in many environments.

For the systems worn on the torso, their physical interface layout follows one of two forms: (1) a back array of vibrators generating straight-line patterns (e.g. Ross et al., 2000; Tan et al., 2003) and (2) a waist belt embedded with vibrators generating absolute point vibrations (e.g. Duistermaat, 2005; Erp et al., 2005; Tsukada et al., 2004). Researchers have reported each of these interfaces as effective.

How to represent tactile spatial information

So far in this chapter, we have finalised that we focus on four types of spatial cues, namely direction, landmarks, confirmation and orientation cues. In order to provide perceptive and distinguishable tactile feedback via the interfaces, we have to understand the limitation of human cognition as well as that of tactile displays. In addition, chosen representation techniques depend largely on the chosen form of wearable devices.

We already know that our system would provide several types of spatial information. It is understandable that one pattern, which is used to represent one thing, e.g. direction, must be different from another pattern, which represents another thing, e.g. landmark. This leads to our fourth RQ.

> ***RQ4: How can we represent spatial information via the chosen device? Specifically, which representation technique should be used for each type of spatial information?***

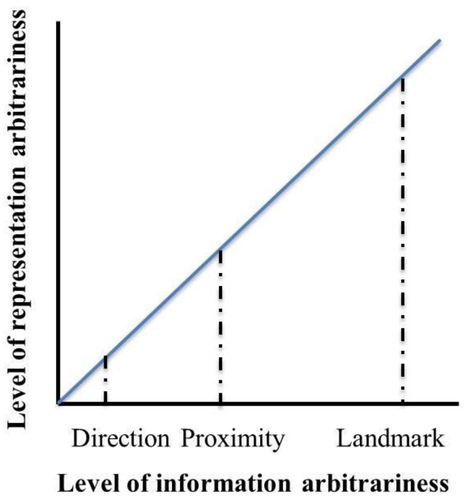

Figure 2.13 Example of Information categories, which cannot be easily conveyed through touch

Problem lies in tactile semantic representation

There are two main approaches to creating informative tactile stimuli: the abstract and symbolic approaches (MacLean, 2008b). Abstract representation focuses on manipulating a stimulus' characteristics, whereas the symbolic approach focuses on the semantic association of stimuli with known metaphors (see Section 2.3.1). Our thesis investigates these approaches for different types of spatial information.

Providing the more arbitrary categories of information via the tactile channel is difficult. The main problem lies in the mapping between ideas (which represent concepts) and their corresponding tactile patterns. The relationship between the level of arbitrariness of information types and their representation is demonstrated in Figure 2.13. An information category like *direction* might be represented easily by simulated straight-line patterns or placements of tactile output devices. The reason is that this spatial metaphor refers to a small set of possible discrete values, which can easily directly map to our perception. For information categories like *distance* and *landmark*, mapping is more problematic. *Proximity* is either measured by distance or time; *landmark* refers to a set of continuous values. The bigger the set of values one category represents, the more arbitrary the mapping becomes. Since our thesis does not focus on proximity, we will omit its discussion.

A representation of landmarks is challenging. Landmarks can be any objects or places on routes that are stationary, distinct and salient (Burnett et al., 2001) (for explanation, see Section 2.1.3). If we were to map landmarks using a symbolic approach, appropriate metaphors would require investigation. For example, it might be possible to draw on a shape metaphor, with each landmark signal represented by a simplified form of its shape. However, such an approach would require a complex hardware layout, a large number of actuators and actuator placements (e.g. Bach-y-Rita et al., 1998).

Too little is known about the exact communicative capacities and appropriate representation of tactile spatial information, unlike our better understanding of association of symbols (visual language) and sounds (auditory language) to their meaning. Since a set of general rules to inform tactile design parameters is not well understood, we will investigate these representation issues in Chapter 3 (for direction, orientation and confirmation cues), Chapter 4 (for landmark) and Chapter 5 (for an integrative evaluation).

When to represent signals

With visual displays, information is always available. On the contrary, tactile communication is designed to grab users' attention at the time that information is needed due to perception limitation of humans and skin adaptability. There is no literature that has mentioned the issue of tactile cue timing, whether it should be delivered time-based or distance-based with reference to each decision point. Although this issue is not our main focus, we attempted to propose the optimum timing thresholds for each information type. We discussed our suggestion along with other representation issues in Chapters 3, 4 and 5.

2.4.3 Usability and user experience issues

So far in this chapter we have listed tactile display design issues. In this section, we will focus on an evaluation of the system. Up until now, there has been no empirical study that evaluates the tactile navigation system which provides multiple types of spatial information on their usability. This leads to our fifth RQ.

> ***RQ5: What is the tactile navigation system's performance?***

Throughout Chapters 3 and 4, we demonstrate that our design of the system achieved usability goals, which include effectiveness, efficiency, safety, utility, learnability and memorability (Sharp et al., 2011).

Theoretically, pedestrians have different purposes in navigation. We assume that they would like to use a navigation aid for either quest or exploratory purposes. Hence, we set out to find the answer. This leads to RQ5.1.

> ***RQ5.1 Does the system help with different navigation purposes?***

We have evaluated our first version of the system and reported the answer to RQ5.1 in the 2nd part of Chapter 3 and Chapter 5 respectively. In addition, we revisited usability goals in the results and discussion parts of Chapter 5.

According to May et al. (2001), direction plays a significant part in navigation completion while landmarks help in building spatial knowledge of the surroundings. Much of tactile navigation research focuses on providing a single type of information (being either direction or distance or their combination). Therefore, they helped primarily with route guidance rather than with developing survey knowledge. With regard to the most basic purpose of pedestrian navigation, which is to travel from a starting point to a destination, generating and comprehending directional information might be enough. Nevertheless, there are different purposes of pedestrian navigation. Hence, a good navigation system should satisfy a variety of navigation purposes, and provide information necessary for those purposes (such as explore and quest). In turn, a good navigation system with appropriate technology should help increase user confidence and improve their navigation performance (Ross et al., 2004). From a study by Ross et al. (2004), visual landmarks assisted users in identifying the precise location of the manoeuvre (i.e. a point at which the user had to follow an instruction). Landmarks help users with poor judgment of distance to be able to navigate with a better performance than if there was no landmark information presented. Results from many studies (i.e. Vinson, 1999; Burnett et al., 2001; Baus et al., 2007) suggested that tactile navigation systems' value could be improved by providing landmark information.

None of the previous research has attempted to provide directional together with landmark information or other types of spatial information. Consequently, our overall research aim is to develop a navigation guidance that provides these two types of crucial information through the touch sense. We would like to discover whether the tactile representation of landmark would hold an analogous effect to users' confidence and performance the same as it does for visual systems. This leads to RQ5.2.

> ***RQ5.2 Can tactile landmark representation "increase/help" with performance/confidence as in visual pedestrian navigation systems?***

We have identified major problems with visual navigation (see Chapter 1 Section 1.1.4). We expected that the tactile navigation system would allow pedestrians' attention to focus on the navigation tasks rather than the usage of the technology. Additionally, we expected that our system would impose fewer cognitive demands than visual-based applications (that impose a high level of cognitive workload for mental orientation and the transfer among different frames of references). This introduces RQ5.3.

> ***RQ5.3 Is there a problem with the transfer of frames of reference with tactile navigation displays?***

Traditionally, HCI has been concerned with usability matters. More recently, the community is also interested in the aspects of user experience with the system, e.g. to be aesthetically pleasing or how it feels and looks. We expected our users' emotions and felt experiences to be desirable[31] ones. We introduce RQ5.4.

> ***RQ5.4 What are user acceptance and perceived usefulness (practicality) of the tactile navigation system?***

The discussion on RQ5.2 – RQ5.4 can be found in Chapter 5.

Finally, we are interested in understanding the way pedestrians would navigate using a unimodal tactile system in an urban environment. Our thesis refers to navigation models proposed by Zhai (1991) and Burnett (1998), which were based on vehicular navigation. We discussed the findings in Chapter 5.

2.5 Summary

This chapter has given an overview of related literature to the design and evaluation of tactile navigation systems including psychophysics of touch, ubiquitous environments and pedestrian navigation, synthetic tactile signals' characteristics and related work. We also listed the detailed description of our empirical plan to investigate both design and usability issues of the system. We referred to the proposed guidelines and theories as a basis for the design of signals and the system.

In summary, this thesis aims to find the best way to convey multiple types of spatial information necessary for pedestrian navigation tasks through artificial tactile feedback on a wearable device. In effect, the result of this work will strengthen our understanding of tactile communication for navigation tasks.

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[31] Desirable aspects of user experiences can be described as: satisfying, enjoyable, engaging, pleasurable, exciting, entertaining, helpful, motivating, challenging, enhancing sociability, supporting creativity, cognitively stimulating, fun, provocative, surprising, rewarding and emotionally fulfilling. On the other hand, undesirable aspects can be described as: boring, frustrating, making one feel guilty, annoying, childish, unpleasant, patronizing, making one feel stupid, cutesy, and gimmicky (Source: Sharp et al., 2007).

Lack of direction, not lack of time, is the problem. We all have twenty-four hour days.

(Zig Ziglar, 1970)

Chapter 3 An Empirical Investigation into Tactile Directional Display

3.1 Introduction

In Chapter 2, we analysed literature on information requirements and derived a limited list of spatial information types necessary for navigation completion. They include four types of spatial data: directions, confirmation cues, orientation cues and landmarks. This list provides an answer to *RQ1: What information types should the tactile navigation display provide to pedestrians?*

This chapter builds upon such information requirements, focusing on the first three types: direction, confirmation cues and orientation cues. An investigation of landmarks and their representation is reported in Chapter 4.

The primary focus of this chapter is the investigation into the display of tactile directional information. The chapter has two aims: (1) to find out the effective form of the display between the two popular types of wearable tactile displays: a back array and a waist belt; and (2) to evaluate our prototyping system in the actual environment for quest navigation.

The chapter begins with the motivation and basis for the study (Section 3.2). Then in Section 3.3, we report results from two direct comparison studies of two wearable devices, which were carried out in late 2007 and early 2008 respectively. Results indicated that the tactile belt allowed participants to perform significantly faster and more accurately than the tactile back array. We then took the waist belt device to develop a prototyping system that provides directional and confirmation cues for *quest*[32] navigation. In late 2008, the system has been evaluated in the field compared with a visual mobile maps application. Section 3.4 reports results of the field comparison study as well as discusses performance-related

[32] Quest involves travel from a familiar place of origin to an unfamiliar destination.

issues. Section 3.5 is a general discussion for both the lab and the field studies. Finally, Section 3.6 summarises the findings of the chapter leading to the next empirical study.

3.2 Basis for the study: motivation and a review of tactile directional displays

In order to reach designated destinations, both sighted and visually impaired users rely comprehensively on directional information, which is used at key decision points, e.g. at turns (Bradley & Dunlop, 2005; May et al., 2003). Additionally, they may use landmarks to identify a point on route and street name to confirm their navigation decisions (see the full list in Table 2.1).

Up to now, studies on tactile navigation displays were proof-of-concept studies demonstrating that the delivery of spatial information via the touch sense is possible (Elliott et al., 2010). Given that the technology has matured, we need to take the study beyond the current state to focus on operational use. Although substantial literature involving a variety of wearable device layouts and tactile representation approaches has been examined, there is no comprehensive comparative study available to inform the designers of the effect of layouts and representation approaches on direction identification performance. We are interested in reviewing and comparing their effectiveness.

In previous research, tactile signals were delivered on different areas of the body to provide cues for orientation and wayfinding both in virtual and real environments (see the full list of various forms of tactile wearable interfaces in Table 2.2).

Of the proposed different locations, we have focused on the wearable systems that use the torso as a display site, specifically the belt-type and the back torso vest devices.

We decided not to consider other areas. We discarded the head area because users reported discomfort wearing the system (Myles & Binseel, 2007). For the systems worn on the shoulders, the size of body contact areas does not afford the display of eight directions and detection suffers by the changing of the wearer’s posture affecting the degree of closeness of the wearable device to the wearer’s body surface, which in turn lowers signal perception (Toney et al., 2003).

Although the wrists and fingers were reported to be the most sensitive perceptible areas compared to other sites such as torso and thighs (Karuei et al., 2011), we did not consider these locations because we predict that users would normally require their hands to be free to perform other activities when interacting in operational environments. For the system worn on the thighs, the ankles and the feet, the locations may not be suitable for actuator placement because they are main organs used for walking. Specifically, users reported low signal detection on thighs, ankles and feet compared to other sites on the body affected by the nature of movement (Hoggan & Brewster, 2006; Karuei et al., 2011).

Other locations being examined for the level of tactile signal perception in a mobile context include stomach, upper arm, and chest (Karuei et al., 2011). Results demonstrated that these locations did not afford good performance compared to the torso area. Consequently, we follow researchers' (Hoggan & Brewster, 2006; Karuei et al., 2011) suggestion that the spine, back torso and waist areas are top candidate sites for displaying directional information.

For the systems worn on the torso, their physical interface layout follows one of two forms: (1) a *back array* of actuators generating straight-line patterns (e.g. Ross & Blasch, 2000; Tan et al., 2003); and (2) a *waist belt* embedded with actuators generating absolute point vibrations (e.g. Duistermaat, 2005; Van Erp et al., 2005; Tsukada & Yasumura, 2004; Heuten et al., 2008). Researchers have reported each of these interfaces as effective.

The back array device displays directions by generating different stimulation patterns on an array of vibrators to create the illusion sensation of a dotted line or a moving direction, known as the "*cutaneous rabbit*" phenomenon or *saltatory* signals (Geldard et al., 1972; Tan & Pentland, 2005). Figure 3.1 demonstrates that the actual stimulation on the left graph creates an illusion sensation shown on the right graph. Most of the wearable tactile interfaces using this approach are in the form of a vest and stimulate the user's back. Tan & Pentland (1997), Young et al. (2003), Tan et al. (2003) and Ross & Blasch (2000) built their interfaces using a 3x3 motor array whilst Ertan et al. (1998) and Tan & Pentland (2001) created a 4x4 layout. Each direction was generated as a simulated line using multiple motors, e.g. vibrating motors in the middle vertical row of the array from bottom to top conveying *straight*. The systems were tested with drawing (Tan et al., 2003), task switching under high workload situations (Hameed et al., 2006) and street-crossing (Ross & Blasch, 2000) tasks. Researchers have reported that tactile interaction intuitively presented spatial information for the drawing tasks (Tan et al., 2003), managed attention during task switching (Hameed et al., 2006) and effectively assisted visually impaired pedestrians in their street-crossing tasks (Ross & Blasch, 2000).

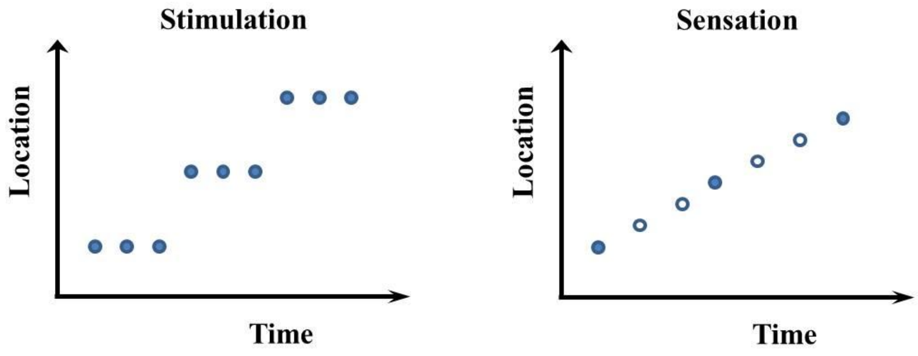

Figure 3.1 The cutaneous rabbit or saltatory signals. A phenomenon where a series of tapping on separated but connected regions of the skin creates a sensation of sequential taps likened to that of a rabbit hopping along the skin (Geldard & Sherrick, 1972; Tan & Pentland, 2001; Tan et al., 2003)

On the other hand, the waist belt interface represents a direction by triggering vibration of an actuator at the corresponding location around the waist. Prototypes are embedded with a number of motors distributed around the waist. The number of actuators varied from six (Heuten et al., 2008; Pielot et al., 2008; Pielot & Boll, 2010a) and eight (Tsukada & Yasumura, 2004; Brill et al., 2004; Van Erp et al., 2005; Duistermaat, 2005; Lindeman et al., 2005; Elliott et al., 2007; Elliott et al., 2010) to 12 (Van Erp, 2001; Svensson & Andersson, 2010) and 15 (Van Erp, 2005) actuators. Each motor represented one of the directions, with each directional signal being generated using one motor. These motors were individually adjusted to account for differences in body shape and size such that each point signifies a represented direction for any particular user. For example, vibrating the motor located at the front in the middle of the waist conveyed *straight*. Evaluation results of the interface suggested that they were practical for conveying directional information in operational environments including pedestrian navigation during daytime (Tsukada & Yasumura, 2004; Pielot et al., 2008), in low visibility environments such as at night in densely forested terrain in both normal and adverse circumstances (Duistermaat, 2005); navigation in visually cluttered environments like in the cockpit of an aircraft (Van Erp et al., 2005), and in vibrating environments as seen in a fast boat (Van Erp et al., 2005). In general, it is reported that tactile direction and spatial orientation cues increased reaction time and an awareness of the task situation as well as stabilised spatial orientation (Elliott et al., 2009).

These two interface designs, the back array presenting a saltatory line and the waist belt presenting absolute points, have dominated research on tactile navigation displays on the torso, with each claiming success as a navigation aid. However, at the time of this research commencement (circa 2007), there was no reported research that directly compares these two different approaches in terms of their performance and subjective preference. Therefore, to inform the design of effective pedestrian navigation systems, we experimentally compared these two established versions of wearable tactile displays. We carried out two lab-based experimental evaluations involving directional pointing and line drawing tasks. In the next section (3.3), we report these two lab-based studies and present findings directly comparing the back array and waist belt approaches.

3.3 Lab-based experimental comparison: a comparative study of array and distributed tactile interfaces for indicating direction

3.3.1 Overview: underlying theories for tactile directional study

After cataloging all relevant work in tactile directional displays fitted on the torso area, an optimisation of hardware design is required prior to the commencement of our comparative experiment. We have seen two variations of the back array (3x3 and 4x4); and four variations of the belt (6, 8, 12 and 15 linear actuators) interfaces. We intend to compare one variation of each type, namely the 3x3 back array and the belt embedded eight actuators; chosen criterion is based on the number of directions that should be presented for wayfinding in the city. According to QSAM (Hernandez, 1994; Shi et al., 2007) and Choremes theory (Klippel, 2003; Klippel et al., 2005), pedestrian navigation in an urban environment concerns a limited set of eight primitive directional elements.

According to Klippel et al. (2004), mental representation of direction concepts in structured space like in the city canyons differ from those[33] in open spaces such as in sea or air navigation. Most city structures have been planned and built with regular geometric shapes such as straight lines, grids, and symmetric radial patterns[34]. Directions in city street networks are usually of homogenous direction models, that is, bisecting directions into equally sized sectors and axes (see examples in Klippel, 2003; Hernandez, 1994). Although, there are parts of the city structure that may not be regularly shaped in grid patterns, humans have developed strategies and mentally conceptualised directional

[33] Direction concepts in sea or air navigation are usually required to be exact angular information.

[34] The lack of variation in the city environments requires signposts to aid orientation (Montello, 2005).

choices in those environments. These strategies can include straightening curved paths, squaring oblique intersections and aligning nonparallel streets (Evans, 1980).

The QSAM's and Choremes' eight direction model provide the basis for the choice of hardware variations for the belt. It is clear that the belt with eight actuators is chosen among all variations because each point perfectly represents each of the potential turning points in such a model. Our prototype should not provide only six points (as seen in Heuten et al., 2008; Peilot et al., 2008; Pielot & Boll, 2010a) because the actual environment could be more complex than this coarse level of granularity design can afford. In one of the six-motor configurations (Pielot et al., 2008), the system was designed to give different degrees of veer by increasing signal intensity. We decide that this may not be practical in the actual environment since it has been reported that humans are not as good at distinguishing amplitude as we are at other signal parameters such as burst duration. We also discard the 12-point and 15-point designs (as seen in Van Erp, 2001; Svensson & Andersson, 2010) because it is not necessary for pedestrians to read directions using the same semantics of fine granularity as military personnel are required to do.

For the back array, both the 3x3 and the 4x4 configurations can afford the delivery of eight *saltatory* directions (see an example in Figure 3.1). In order to create the cutaneous illusion, the minimum array size is 3x3 (Geldard & Sherrick, 1972) and could possibly go up to 9x9[35]. However, there were only two variations of the existing prototypes being evaluated. Since our main interest is not on the array optimisation, we chose the 3x3 over the 4x4 structures, the reason being the majority of previous studies were done with the 3x3 configuration.

We closely followed the designs of both established interfaces, both in terms of the form of the wearable devices and the tactile stimuli patterns used for each. We wished to investigate which of the two approaches is more effective and which is more preferred by users. Given the physical differences between the two interfaces, we compared them on a

---

[35] On average, an adult human has a body surface area (BSA) of between 16000 – 19000 square centimetres (cm^2), with 9% being the upper back torso (Mosteller, 1987; Wedro, 2011). An illustration of percentage of BSA is given in Figure 3.2. If we assume that the average surface area of an adult is 16,000 $cm^{2,}$ the upper back torso could be 1,440 cm^2, that is approximately 38x38 cm. The array size of 9x9 reaches the maximum thresholds of tactile spatial resolution on the back torso of an average adult who has a BSA of 16,000 cm^2, given the actuator inter-spacing of at least 40 mm – the two-point threshold on the back torso (Weinstein, 1968).

number of different tasks, experimental settings and measures, in an attempt to eliminate bias and to balance the nature of the tactile feedback with the task requirements.

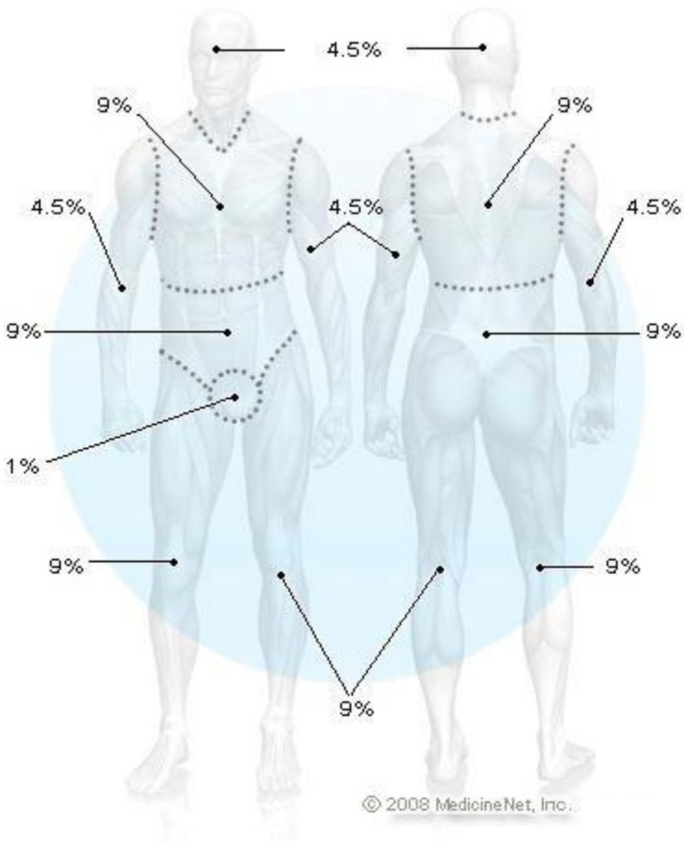

Figure 3.2 Percentage of body surface area (Source: Medicine Net, Inc., 2008)

In our first lab-based experiment, which we carried out in late 2007, we used a directional pointing task because it requires similar skills to those needed when maintaining spatial orientation whilst navigating in many real environments, e.g. the ability to maintain one's "sense of direction" in order to remain heading in the desired destination (Ross & Blasch, 2000). In the second lab experiment, taking place in early 2008, we used a line drawing task because it requires similar skills to those needed when using a map-based navigation system, e.g. the ability to interpret the understanding of directions into two-dimensional representations (Yao et al., 2007) and the ability to associate one's current view of the world to its location in the map (Aretz et al., 1991).

3.3.2 Research questions

Both the back array and the waist belt devices have their proponents and each has been reported as successful in previous independent experimental trials. Our comparative studies of both interfaces address the following research question:

RQ3: What is the effective form of tactile displays for pedestrian navigation?

In the case of representing direction, a series of lab studies also addresses:

RQ4: How can we represent spatial information via the chosen device? Specifically, which representation technique should be used for direction, confirmation and orientation cues?

3.3.3 Method: equipment, tactile stimuli and participants

Equipment

Our lab studies compared the back array with the belt tactile interfaces for indicating directions.

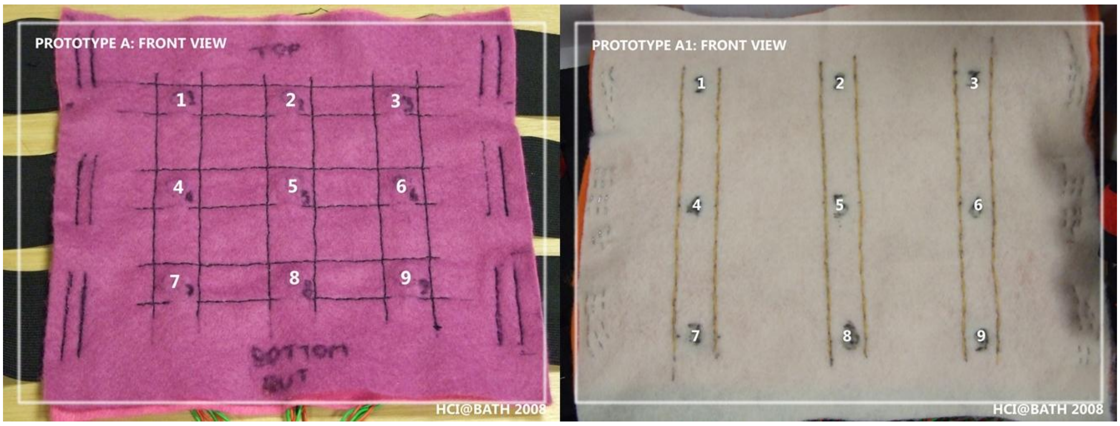

Figure 3.3 A 3x3 back array: A – a 50mm, A1 – a 80mm layouts. Each numerical digit is an actuator number.

For the 3x3 back array, we had to decide the hardware configuration, specifically on the distance between actuators, because previous work had tested different distance values. Tan et al. (2003) reported that different array sizes could affect performance; specifically, petite participants performed better with an array with an inter-motor distance of 50 mm whilst bigger participants performed better with a bigger array (inter-motor distance of 80 mm). Geldard & Sherrick's (1972) research suggests that vibrators in a back array should be spaced at least 40 mm but no greater than 100 mm to create a "line effect" as saltatory signals. This result is supported by Van Erp's (2005b) study where it was found that the spatial acuity on the torso is relatively uniform in the order of 20-30 mm and the system can benefit from a larger distance between actuators. With little other evidence, there is no established optimum value for inter-actuator distance. Therefore, for our initial experiments we built and tested two sizes of the back array: a 50mm and an 80mm inter-spacing layout (see Figure 3.3). Our 50 mm back array (Figure 3.4), consisted of 9 actuators mounted into a fabric pad in a 3-by-3 array. The motors had an equal inter-spacing of 50 mm. Our 80 mm back array was similar in shape but had an inter-spacing distance between motors of 80 mm.

The waist belt tactile interface consisted of eight motors mounted in a belt (Figure 3.5). Following previous research (e.g. Van Erp et al., 2005; Tsukada & Yasumura, 2004), the actuators had an *unequal* interspacing (from 50 mm to 130 mm) to account for participants' varying body shape and size[36].

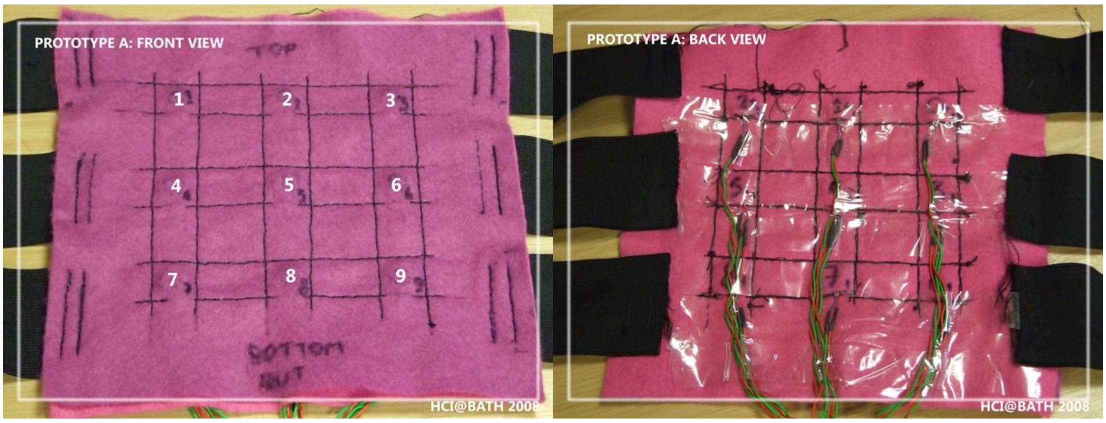

Figure 3.4 A 3x3 back array, front and back view. Each numerical digit is an actuator number.

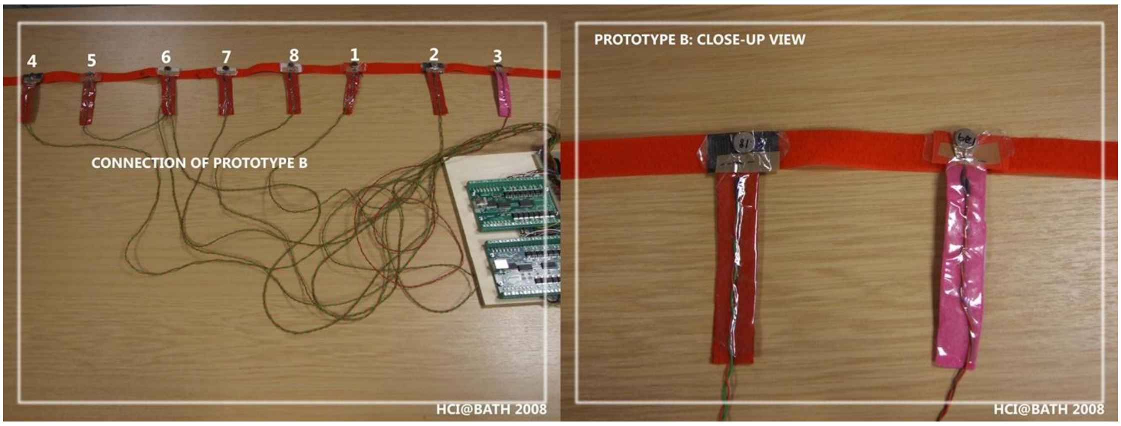

Figure 3.5 Vibrating actuators on a waist belt

To summarise, the prototypes stimulated the waist and the back area; the size of each body contact area is 10mm (i.e. the size of the actuator). All the interfaces were worn over light clothing, e.g. a t-shirt.

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[36] That is to say, if we assume that the shape of a human body is an ellipse, angles (ƒÆ) between pairs of motors are identical (ƒÎ/4) where x = A cos ƒÆ, y = B sin ƒÆ.

The main controller unit was built using two 0/16/16 interface kit controllers manufactured by Phidgets (http://www.phidgets.com). The vibrating points were built using VPM2 vibrating disk motors manufactured by Solarbotics (http://www.solarbotics.com). The motors were 10 mm in diameter and were connected to the controller's digital output channels. Motor vibration was powered by a 6v battery and controlled by an additional custom-built controller switch. All parts described are demonstrated in Figure 3.7. Figure 3.8 shows the actual system setup.

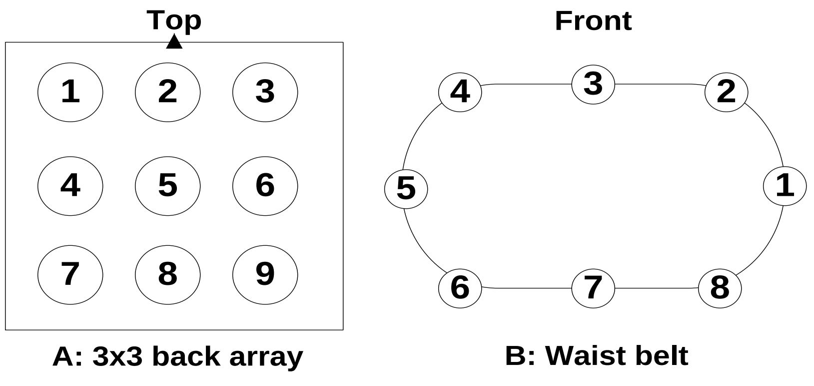

Figure 3.6 Side-by-side comparison of the two interfaces: A-the array worn on the back torso and B-the belt worn around the waist

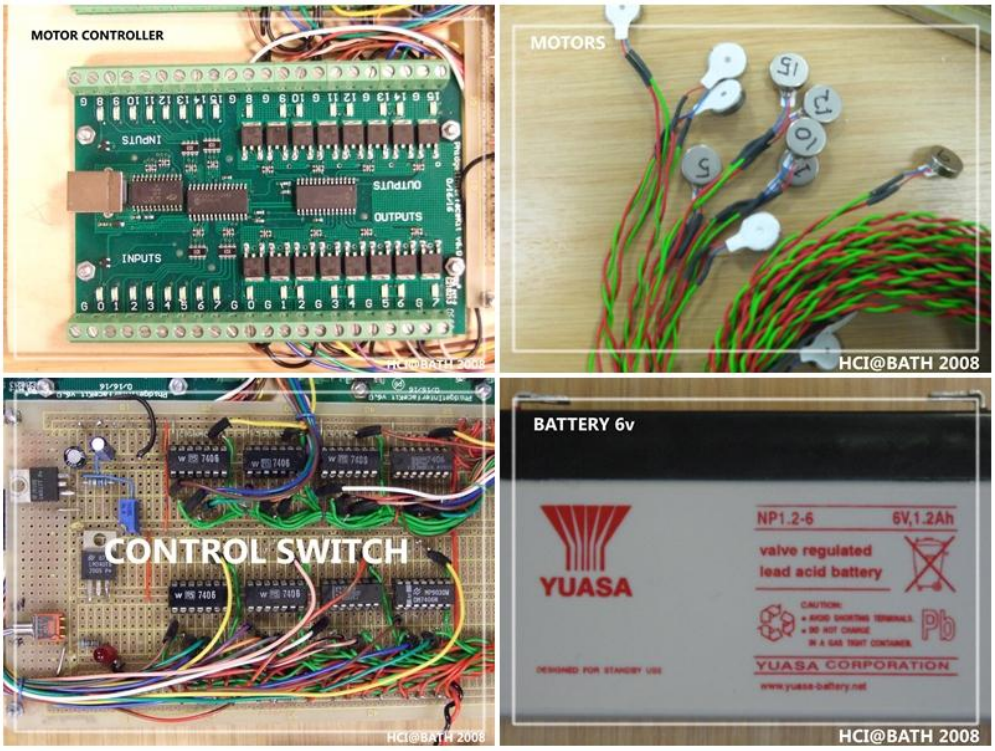

Figure 3.7 Top left – the Phidgets main controller unit, Top right – Solarbotics disk motors, Bottom left – a custom built controller switch and Bottom right – a 6v battery

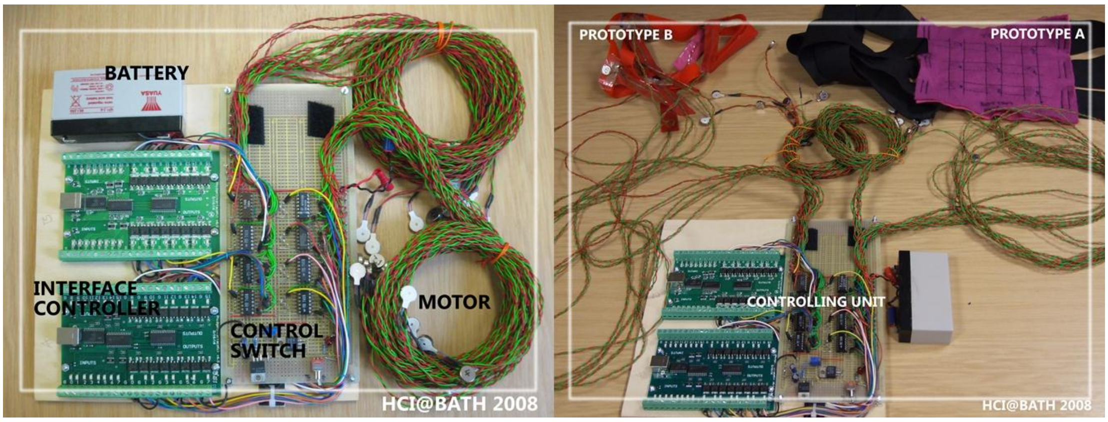

Figure 3.8 Left – the connection of a controlling unit with motors, Right – The final products

The controller was connected to a computer via a USB port. The control software was written in Java. Figure 3.9 demonstrates the system architecture.

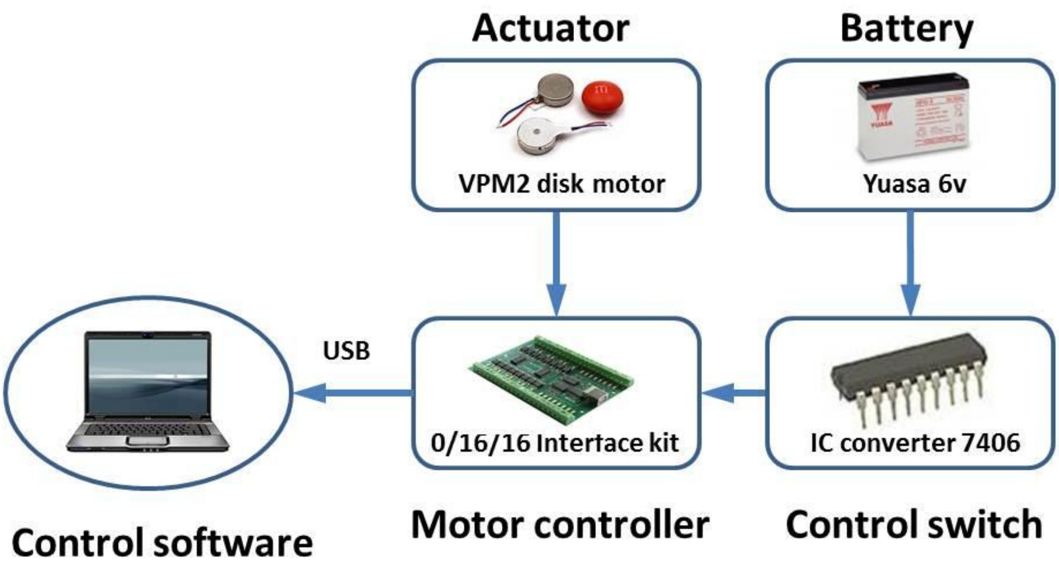

Figure 3.9 System Architecture

Tactile stimuli

The design of our tactile stimuli drew mainly on previous research's design (e.g. Geldard, 1985; Tan et al., 2003; Jones & Sarter, 2008) in combination with psychophysics described in Chapter 2 and tactile interaction design guidelines (see the list in Chapter 2).

For frequency value, we followed suggestions that the square wave form is the most intense detectable threshold and that the optimum value is constant at 200 Hz (Jones & Sarter, 2008; Tan et al., 2003; Van Erp, 2005b; Van Erp, 2002).

For the three aspects of time variables (i.e. the burst duration of the stimulus, the pulse repetition and the number of pulses) of both layouts, we designed two sets of tactile stimuli: set A (Table 3.1) for the 50 mm and the 80 mm back arrays, and set B (Table 3.2) for the belt. Stimuli set A involved actuation of three motors and consisted of four repetitions of signals at 50 ms pulse and inter-pulse on each motor, i.e. 12 pulses in total for each stimulus (see example in Figure 3.10). The pattern for stimuli set B involved actuation of one motor and consisted of 12 repetitions of signals at 50 ms pulse and inter-pulse duration (see example in Figure 3.11). Hence, the number of pulses and duration of signal were the same across both stimuli sets.

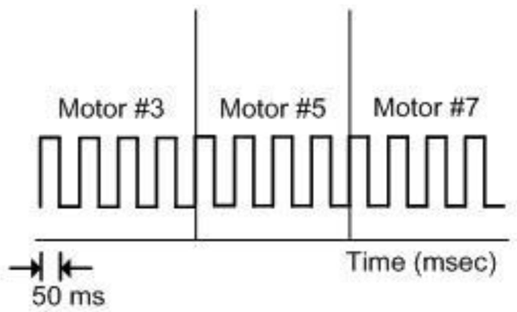

Figure 3.10 An example of sharp left signal of stimuli set A, from the controller

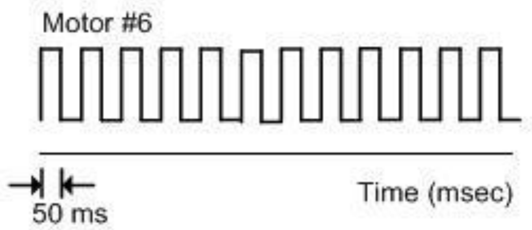

Figure 3.11 An example of sharp left signal of stimuli set B, from the controller

For the definition of directions, we followed linguistic externalisation in Choremes' direction model (Klippel, 2003; Klippel et al., 2005). Direction is defined with respect to the body trunk (i.e. egocentric frame of reference[37]), containing seven mental concepts of

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[37] During the course of navigation, humans have to maintain their orientation as they move. This orientation involves a mixture of knowing ones' location and directions with reference to particular features, concrete or abstract, in the environment (Montello, 2005). This reference can be classified as egocentric or exocentric (Hart & Moore, 1973; Montello, 2005). The egocentric system codes location relative to one's body whilst the exocentric codes relative to cardinal directions or latitude/longitude coordinates.

route direction elements (see Figure 3.12). In Choremes, direction opposite to the heading path is separately considered as ‘back’.

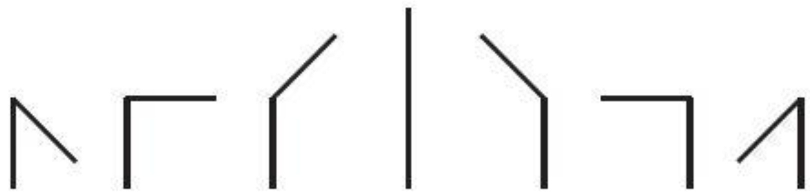

Figure 3.12 The seven wayfinding choremes’ graphical externalisation. Their linguistic externalisation are known as sharp right, right, half right, straight, half left, left and sharp left accordingly.

Table 3.1 Stimuli set A’s signal patterns for the back array

Stimuli code	Signal pattern	Direction
A1	444455556666	Right
A2	666655554444	Left
A3	222255558888	Back
A4	888855552222	Straight
A5	111155559999	Sharp right
A6	333355557777	Sharp left
A7	777755553333	Half right
A8	999955551111	Half left

Number in signal pattern represents motor number in Figure 3.6A

Table 3.2 Stimuli set B’s signal patterns for the belt

Stimuli code	Signal pattern	Direction
B1	111111111111	Right
B2	222222222222	Half right
B3	333333333333	Straight
B4	444444444444	Half left
B5	555555555555	Left
B6	666666666666	Sharp left
B7	777777777777	Back
B8	888888888888	Sharp right

Note: number in signal pattern represents motor number in Figure 3.6B

To sum up, stimuli set A (Table 3.1) contained eight saltatory signals representing the egocentric directions *sharp right, right, half right, straight, half left, left, sharp left, and back*. Stimuli set B (Table 3.2) represented the same eight directions based on the location of the motors around the participant's waist, with *straight* represented by the front centre actuator, i.e. actuator number three.

Participants

In experiment 1, there were 16 participants, 12 males and 4 females, with an average age of 25. In experiment 2, there were a different group of 16 participants, 7 males and 9 females, with an average age of 29. All participants reported no irregularity with tactile perception on their back and around their waist at the time of the experiment. We established from pre-test questionnaires that all participants understood the concept of "direction" and had no difficulties identifying them. They had never previously worn or experienced tactile displays.

We were aware that the body size of participants may have an effect on the results. Therefore, we have recruited participants with a relatively equal distribution in terms of size. In experiment 1, the smallest participant had a 67 cm waist size and the largest was 106 cm. Mean waist was 86.94 cm with SD 10.90. In experiment 2, the smallest participant had a 69 cm waist size and the largest was 114 cm. Mean waist size was 87.25 cm with SD 11.90. There were nine participants having a waist size below the mean in each experiment.

In both experiments, participants used interfaces in random order.

Overview of lab-based studies

Table 3.3 shows a summary of a series of lab-based empirical comparative studies for tactile directional displays. In the first experiment, we evaluated three wearable devices: a 50mm array, an 80mm array and a waist belt. Hence, there are three conditions. Results from experiment 1 showed that the 80mm array allowed significantly better performance than the 50mm layout. Therefore, we further compared the 80mm with the waist belt in experiment 2 for drawing tasks. Experiment 2 attempted to eliminate any bias occurring in experiment 1 by having participants draw on both horizontal and vertical planes. We are also interested in finding out whether a corresponding visual display will affect direction identification performance. As there are two wearable devices (the array and the belt) with two levels of the presence of a visual display (with/without) and two levels of the display's orientation planes (vertical/horizontal); consequently, there are eight experimental conditions in experiment 2.

Table 3.3 An overview of lab-based experiments

Experiment	Tasks	No of prototypes being evaluated	No of conditions
Experiment 1	Pointing	3 (50mm array, 80mm array, waist belt)	3
Experiment 2	Drawing	2 (80mm array and waist belt)	8

Table 3.4 An overview of prototypes being evaluated

Prototype layout	Body contact area	Representation technique	Stimuli use
50mm Array	Back torso	Saltatory line	Set A
80mm Array	Back torso	Saltatory line	Set A
Waist belt	Around the waist	Absolute point	Set B

An overview of prototypes being evaluated is listed in Table 3.4.

3.3.4 Experiment 1: Pointing task

Procedure

In experiment 1, we investigated whether performance with the three interfaces, namely the 50mm and 80mm arrays and the waist belt, would differ for a pointing task in which participants identified perceived directions by touching corresponding sensors on surrounding walls. We compared a range of performance measures: response time, correctly perceived directions (accuracy), failure to identify any direction for a given stimulus (breakdowns), and incorrectly identified directions (errors). We established from pre-test questionnaires that all 16 participants understood the concept of "direction" and had no difficulties identifying them. Participants used all three interfaces in random order to counterbalance any learning effect. Although the number 16 was not perfectly compensated for the three conditions, a slight difference in the number of participants should not create substantial data analytic or interpretative problems (Reis & Judd, 2000).

For the 50 mm and 80 mm back arrays, the middle column of the array was placed along the midline of the body to avoid the spinous processes of the thoracic vertebrae (i.e. the concave area along the spine). Velcro straps were fastened comfortably tight for all motors to have good contact with the back area. Fitting the waist belt was done carefully. The motors' locations were individually adjusted to ensure that all motors were located at the appropriate body sites to denote the eight directions correctly for each participant.

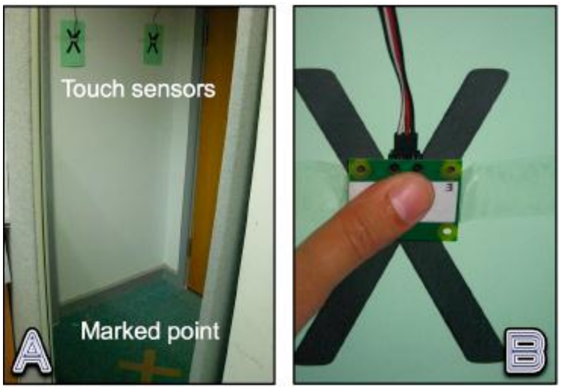

Figure 3.13 A: A side view of the experiment room, with a marked point at the centre of the room. There are 8 touch sensors denoting 8 directions, each has equal distance from the marked point. B: Touching the sensor.

Participants were given a demonstration of how they would receive tactile stimuli via each prototype but were given no other training. The reasons were that we wanted (1) to learn about users' initial reaction to and their preferences between two forms of technology that were new to them, (2) to discover how well they could intuitively (i.e. without extensive training) interpret the meanings of different tactile patterns, and (3) to discover how usable the interfaces were without training. Usually, novel consumer technologies typically do not come with extensive, or often any, training because usability is a key factor in successfully introducing new technology. Furthermore, the tasks carried out in the experience were not too complex, i.e. with no training participants were still able to complete the tasks.

During the trials, participants stood at a marked point in the middle of a closed square room (Figure 3.13A), which had eight touch sensors on the walls denoting the eight directions. All participants were positioned facing in the *straight* direction. When the experiment started, the tactile stimuli were generated. Participants responded to the directions they perceived by tapping on the corresponding touch sensor on the wall (Figure 3.13B). Each participant responded to eight stimuli for each interface. Response direction and response time (in ms) were automatically logged. Response time was the duration between the end of each stimulus and the participant's response to it. Participants were instructed that they could take as much time as they wanted to identify each perceived direction, were allowed to make a guess if they were uncertain, and could skip any signal if they were unable to identify a direction from the stimulus.

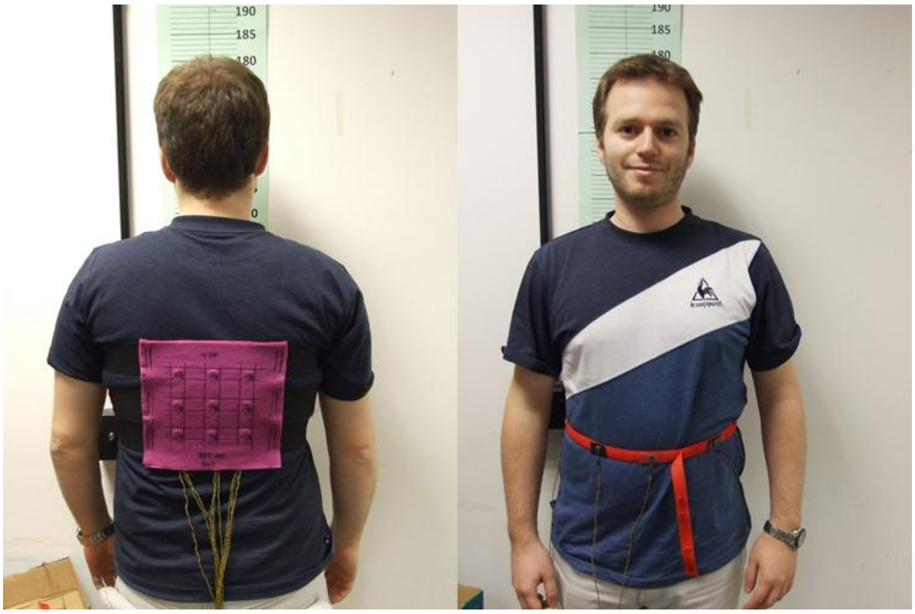

Figure 3.14 Left: a participant wearing the 50mm array. Right: a participant wearing the belt.

We predicted that, although the signal durations were the same, it would take longer for users to interpret the tactile flow generated by the back array than to interpret the absolute point generated by the belt. This is because one must remember the start and end points of the tactile flow and decode it to a direction before responding, and is consistent with Gallace et al.'s finding (2006) that reporting and interpreting several stimuli positions required more time than simply reporting the number of presented stimuli.

Thus, we hypothesised (*H1*) that the belt would allow participants to identify directions faster than the arrays. However, there was no *a priori* evidence on which to base predictions of differences in the other performance measures.

Results

Overall accuracy and response time analysis

The mean of performance measures is shown in Table 3.5. A one-way repeated-measure ANOVA with Interface as the independent variable was used to analyse the results.

For the accuracy scores (Table 3.5 first row), Mauchly's test indicated that the assumption of sphericity had been violated ($X^2(2) = 7.71$, $p < 0.05$); therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.70$). Results showed a significant effect by tactile interface on accuracy, $F(1.41, 21.08) = 90.05$, p < 0.002. Post hoc Bonferroni pairwise tests revealed significant main effects between the 50 mm array and the belt ($p < 0.002$), between the 80mm array and the belt ($p < 0.002$), and between the 50 mm and the 80 mm arrays (p = 0.002). The results suggest that participants performed best using the belt and worst using the 50 mm array.

Table 3.5 Mean Accuracy, Breakdowns, Errors and Response Time across 3 Tactile Interfaces

	50mm Array	**80mm Array**	**Waist Belt**
Accuracy	4.50 (0.82)	5.44 (1.21)	7.62 (0.50)
Errors	2.81 (1.17)	2.38 (1.26)	0.38 (0.50)
Breakdowns	0.69 (0.87)	0.19 (0.54)	0.00 (0.00)
Time	4.12 (1.24)	2.61 (0.67)	1.86 (0.68)

Scores: n of 8, Time: in seconds. SDs in parentheses.

Participants made most errors (Table 3.5 second row) with the 50 mm array and fewest with the belt. A one-way repeated-measures ANOVA found a significant effect by tactile interface on errors, $F(2,30) = 43.52$, $p < 0.002$. Post hoc Bonferroni tests showed significant effects between the 50 mm array and the belt ($p < 0.002$), and between the 80 mm array and the belt ($p < 0.002$). There was no significant difference between the 50 mm and the 80 mm arrays ($p = 0.39$).

For breakdowns (i.e. failure to identify a direction, Table 3.5 third row), a one-way repeated-measures ANOVA found a significant effect by tactile interface on breakdowns, $F(2,30) = 6.53$, $p < 0.05$. Post hoc Bonferroni pairwise tests showed a significant main effect between the 50 mm array and the belt ($p < 0.05$). There was no significant difference between the 80 mm array and the belt ($p > 0.05$) or between the 50 mm and the 80 mm arrays ($p > 0.05$).

Mean response times are shown in the fourth row of Table 3.5. Mauchly's test indicated that the assumption of sphericity had been violated ($X^2(2) = 10.77$, $p < 0.05$); therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε = 0.65). A one-way repeated-measures ANOVA demonstrated a significant effect by tactile interface on response time, $F(1.30, 19.52) = 31.80$, $p < 0.002$. Post hoc Bonferroni pairwise tests showed significant effects between the 50 mm array and the belt ($p < 0.002$), between the 80 mm array and the belt ($p < 0.002$) and between the 50 mm and the 80 mm arrays ($p = 0.001$). The results suggest that participants responded fastest using the belt and slowest using the 50 mm array.

Accuracy and response time analysis by stimulus

Further detailed analysis on each direction was carried out on accuracy scores and response time (see Figure 3.15 and 3.16). Participants reacted fastest with the belt, then the 80 mm array and slowest with the 50 mm array for all directions.

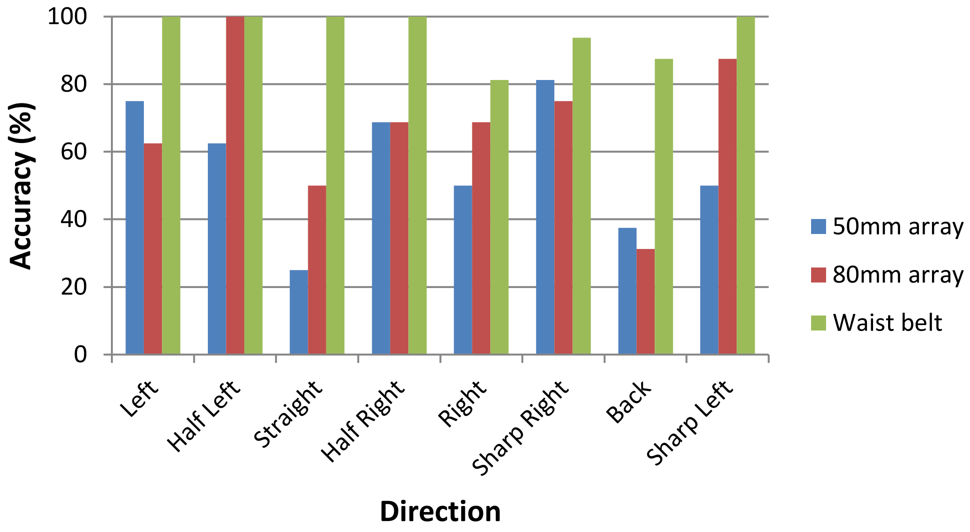

Figure 3.15 Accuracy of responses (%) for all directions with the 50 mm array, the 80 mm array and the waist belt.

For both array prototypes, the data were statistically analysed using a one-way repeated-measure ANOVA. The results showed: no significant difference in participants' accuracy with different stimuli in the 50mm array, $F(5.55, 83.23) = 2.09$, $p > 0.05$; and a significant difference in the 80mm array condition, $F(4.31, 64.60) = 3.94$, $p < 0.05$. For the 80mm array, post hoc Bonferroni pairwise comparison showed a significant effect between directions *back* and *half left* ($p < 0.05$). There was no significant difference between other pairs of directions ($p > 0.05$). In terms of time performance, there was no significant difference for both array conditions ($p > 0.05$). Based on descriptive data, participants performed worst in accuracy and response time with vertical saltatory signals (*straight* and *back).* This might be due to an effect of the neurological gap on participants' backs (Tan et al., 2003). On average, they performed faster and more accurately with all diagonal saltatory signals (*half right, half left, sharp right* and *sharp left*). For the 50 mm array, the orientation of inaccurate answers ranged widely from 45 to 180 degrees both to the left and to the right of the intended direction, while the 80 mm array ranged from 45 to 135 degrees.

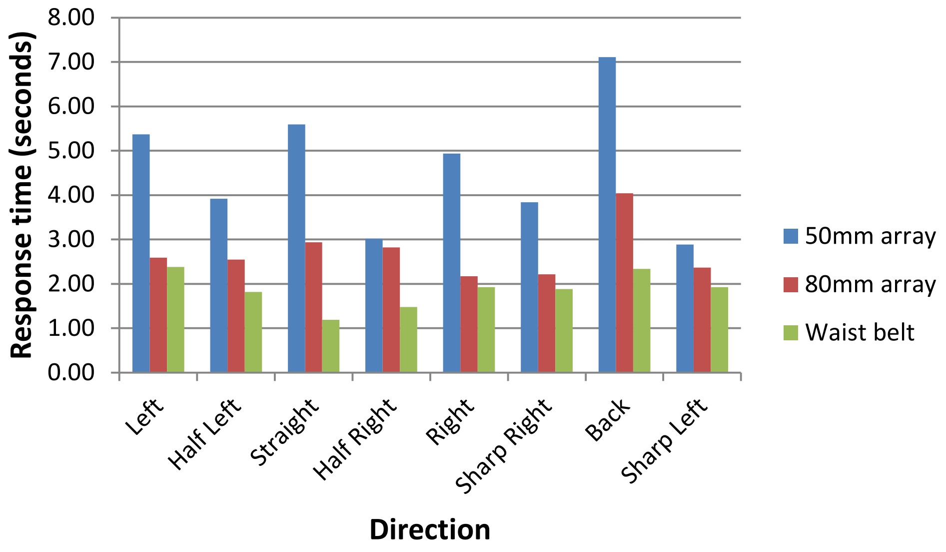

Figure 3.16 Response time (in seconds) for all directions with the 50 mm array, the 80 mm array and the waist belt.

Using the belt, there was no significant difference in participants' accuracy, $F(2.38, 35.67) = 1.91$, $p > 0.05$, and response times, $F(2.19, 19.67) = 2.24$, $p > 0.05$, with different stimuli. Almost all incorrect answers were 45-degree errors (e.g. responding *back* for the *sharp right* stimulus), with only one 180-degree error. Participants made the highest number of errors with *right*, *back* and *sharp right* respectively. A detailed analysis of the data reveals that the more petite participants contributed to this part of the results.

Other results

Previous research (Tan et al., 2003) has suggested that body size has a strong relationship with accuracy in detecting tactile stimuli. Hence, we performed a Pearson's correlation analysis between body size and accuracy for all prototypes. For the 50 mm ($r = 0.38$) and 80 mm ($r = 0.40$) arrays, no significant correlation was found between body size and accuracy in each case ($p > 0.05$). For the belt, the correlation coefficient was significantly positive ($r = 0.70$, $p < 0.002$). In other words, when wearing the waist belt, participants with a bigger body could identify tactile stimuli more accurately than smaller participants.

In addition to the relationship between body size and performance, we were interested in the relationship between sex and performance. We performed a Pearson's correlation analysis. For all prototypes, no significant correlation was found between sex and accuracy in each case ($p > 0.05$).

Participants reported that when wearing the 50 mm and 80 mm array prototypes they had to remember where the vibration started and where it ended in order to interpret the line, and then respond. This may be a reason for the significantly slower response times for the array prototypes.

Although participants reported that it was easier to interpret the stimuli with the waist belt, one participant reported having looked down at the location of the motors on her body before touching the wall sensors. In this case, unsurprisingly, her response times were longer than other participants.

We also observed that the waist belt participants had difficulty differentiating directions on their back area, e.g. *back* and *sharp right*. This kind of error tended to occur when a user, especially a small one, made a large error in point localisation, e.g. of the order of 150 mm. Then he or she experienced difficulty in deciding between the two immediately adjacent motors, sometimes failing to identify the correct one. One of the possible reasons could be the difference in sensitivity to touch stimulation between a human's back and front (Schiffman, 1976; Tsukada & Yasumura, 2004).

Table 3.6 Mean Scores of Subjective Perception and Interpretation of Tactile Stimuli

	50mm Array	**80mm Array**	**Waist Belt**
Perception	1.94 (0.93)	2.69 (0.70)	3.19 (0.54)
Interpretation	1.75 (0.68)	2.19 (0.75)	3.94 (0.57)

Scores: n of a 5 point Likert scale, 1 is low, 5 is high. SDs in parentheses.

At the end of the first experiment, participants were asked to rate how strongly they felt the vibrations (*perception level*) and how well they could interpret the perceived vibration sensations to directions (*interpretation level*). Mean scores of subjective *perception* and *interpretation* of the tactile stimuli for different prototypes are shown in Table 3.6 (first and second row respectively). Perception refers to how clearly participants felt the tactile stimuli. Interpretation refers to the degree to which participants understood the meaning of the given tactile information in order to identify directions. These rating values have a strong relationship with users' performance, i.e. the higher the ratings, the higher the performance.

When asked to choose between the 50 mm and the 80 mm array, 13 participants (81%) chose the 80 mm array. The three participants (19%) who picked the 50 mm array were petite users. These 3 participants stated that the size of the 50 mm array seemed to fit better than the bigger array.

When asked for their preferred wearable interface between the arrays and the belt, all participants preferred the waist belt. Their reasons included: the belt is easy to use, easy to understand, worn easily, worn on the waist which they preferred to the back, smaller in size, and gave them confidence in identifying directions because the signals were precise and required little effort to memorise and interpret.

In summary, we accepted our hypothesis *H1* since the results of experiment 1 show that participants performed fastest with the belt. The results also indicated that participants performed significantly more accurately with the belt than with the arrays.

3.3.5 Experiment 2: Line drawing task in two planes

Procedure

In experiment 2, we investigated whether performance between the two wearable layouts would differ for a line drawing task. In addition, because of the significant differences in the results found in experiment 1, we wanted to investigate if the pointing task in experiment 1 might have favored the belt layout since the plane of the belt vibrators matched the plane of the wall sensors. Hence, in experiment 2 we also varied the plane in which participants responded.

The experimental conditions involved drawing arrowed lines, indicating perceived directions, on a touch screen with one of two orientations: vertical and horizontal. We hypothesised that participants would perform better when the plane of the prototype matched the plane of the screen (*H2*). Thus, participants would perform better with the back array when the task involved drawing directed lines on a vertical screen. On the other hand, they would perform better with the belt when the task involved drawing directed lines on a horizontal screen.

In addition, we investigated the effect of adding a complementary display on the performance of both interfaces. As Carter & Fourney (2005) suggested that using other senses as cues may support tactile interaction, we introduced a visual display as an experimental factor with 2 levels. In the first level, the touch screen presented a blank display on which participants drew their directed line (Figure 3.17A). In the second level, the touch screen presented a visual display of a map indicating eight directions from a central roundabout, corresponding to the eight directions indicated by the tactile stimuli

(Figure 3.17B). We predicted that the visual display of the map would aid the participant in interpreting and responding to the tactile stimulus.

In summary, in experiment 2 we examined the effect of (1) the plane of output display and (2) the presence or absence of a visual map display on performance with the array and belt tactile interfaces. The experimental hypotheses were as follows.

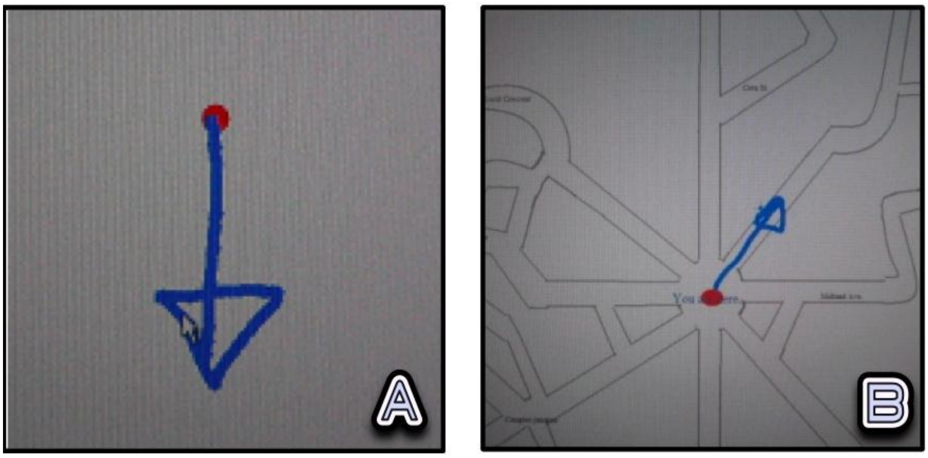

Figure 3.17 A: Line drawn by a participant on the blank display. B: Line drawn by a participant on the map display.

H2. Performance will be better when the plane of the tactile stimuli matches the plane of the responses, specifically:

> *H2a*. Participants will perform better with the back array when the task involves drawing lines on a vertical screen;
>
> *H2b*. Participants will perform better with the waist belt when the task involves drawing lines on a horizontal screen;

H3. Participants will perform better with the map display than with the blank display.

Table 3.7 Experiment 2's Conditions and Their Code Names

80 mm Array				**Waist Belt**			
Vertical screen		**Horizontal screen**		**Vertical screen**		**Horizontal screen**	
Blank (C1)	Map (C2)	Blank (C3)	Map (C4)	Blank (C5)	Map (C6)	Blank (C7)	Map (C8)

For experiment 2, the 80 mm array and the belt were used. We discarded the 50 mm array since experiment 1 had found it to be significantly less effective than the 80 mm array. Tactile signals and methods were the same as those used in experiment 1.

A new set of 16 participants took part in experiment 2. Participants used both tactile interfaces. They were instructed to stand at a marked point which was approximately 200 mm away from the vertical screen condition; and 130 mm away from the lower edge of the screen in the horizontal display condition. The height of the screen was adjusted to suit individuals for vertical and horizontal conditions. The mark point and height adjustment of the screen were designed to maintain participants' body position as always straight. The order of conditions was counterbalanced.

Stimuli set A and B were generated by the 80 mm array and the belt respectively. There were eight conditions, C1-C8, as shown in Table 3.7. Participants responded to the directions they perceived by drawing arrows with a stylus on the touch screen. Each participant responded to eight stimuli for each condition. We did not design the experiment for each condition to be repeated because we used a within-group design where each participant ran eight conditions that took place for about one hour in total. We were concerned that participants being stimulated with tactile feedback for a very long time could suffer from fatigue (see Schiffman, 1978). We did not want the impact of fatigue and frustration to influence performance.

Response direction and time were automatically logged. Response time was the time that elapsed between the end of each stimulus and the response to it. Participants were given a demonstration of how they would receive tactile stimuli via each interface but were given no other training—for the same reasons stated above for the first experiment.

Results

Overall accuracy and response time analysis

The mean accuracy, error, breakdowns and response times for the 80 mm array and the belt are shown in Tables 3.8 and 3.9. The data were analysed using a three-way repeated-measures ANOVA with *tactile interface*, *screen orientation* and *visual display* (Table 3.7 top, second and third rows respectively) as the independent variables.

There was no significant interaction effect between *tactile interface* and *screen orientation* on accuracy $F(1, 15) = 0.54$, $p > 0.05$, errors $F(1, 15) = 0.05$, $p > 0.05$, breakdowns $F(1, 15) = 1$, $p > 0.05$, or response time $F(1, 15) = 1.74$, $p > 0.05$. These results tell us that the effects of the different tactile interfaces did not vary depending on the touch screen's orientation.

Post hoc Bonferroni pairwise comparisons showed that accuracy was significantly better with the belt than with the array in each case (p < 0.002); errors were significantly fewer with the belt than with the array in each case (p < 0.002); and response time was significantly quicker with the belt than with the array in each case (p < 0.002). No significant difference was found on breakdowns.

Table 3.8 Mean Performance for Vertical Screen Conditions

	80 mm Array *Vertical* Screen		**Waist Belt *Vertical* Screen**	
	Blank (C1)	**Map (C2)**	**Blank (C5)**	**Map (C6)**
Accuracy	5.06 (1.84)	5.25 (1.65)	7.44 (0.63)	7.19 (1.11)
Error	2.81 (0.63)	2.44 (1.59)	0.50 (0.63)	0.75 (1.07)
Break-down	0 (0.00)	0.31 (0.60)	0 (0.00)	0.06 (0.25)
Time	2.13 (0.50)	2.08 (0.83)	1.40 (0.37)	1.54 (0.67)

Scores: n of 8, Time: in seconds. SDs in parentheses.

Table 3.9 Mean Performance for Horizontal Screen Conditions

	80 mm Array *Horizontal* Screen		**Waist Belt *Horizontal* Screen**	
	Blank (C3)	**Map (C4)**	**Blank (C7)**	**Map (C8)**
Accuracy	5.63 (1.75)	5.63 (1.67)	7.5 (0.63)	7.63 (0.89)
Error	2.25 (1.65)	2.31 (1.66)	0.44 (0.63)	0.25 (0.58)
Break-down	0.12 (0.34)	0.06 (0.25)	0 (0.00)	0.12 (0.50)
Time	2.08 (0.37)	2.21 (0.59)	1.28 (0.35)	1.41 (0.36)

Scores: n of 8, Time: in seconds. SDs in parentheses.

Thus, hypothesis *H2* was rejected since participants performed significantly faster and more accurately with the belt than with the array whether they had a vertical screen or a horizontal screen.

A three-way repeated-measures ANOVA was run to compare blank displays and visual map displays on accuracy, response time, breakdowns and errors. No significant effect of display type was found on accuracy $F(1, 15) = 0.01$, $p > 0.05$, response time $F(1, 15) = 0.06$, $p > 0.05$, breakdowns $F(1, 15) = 2.56$, $p > 0.05$, or errors $F(1, 15) = 0.14$, $p > 0.05$. Thus, we rejected hypothesis H3 since display type had no effect on performance.

Accuracy and response time analysis by stimulus

We performed a further analysis on accuracy and response times with respect to the stimuli.

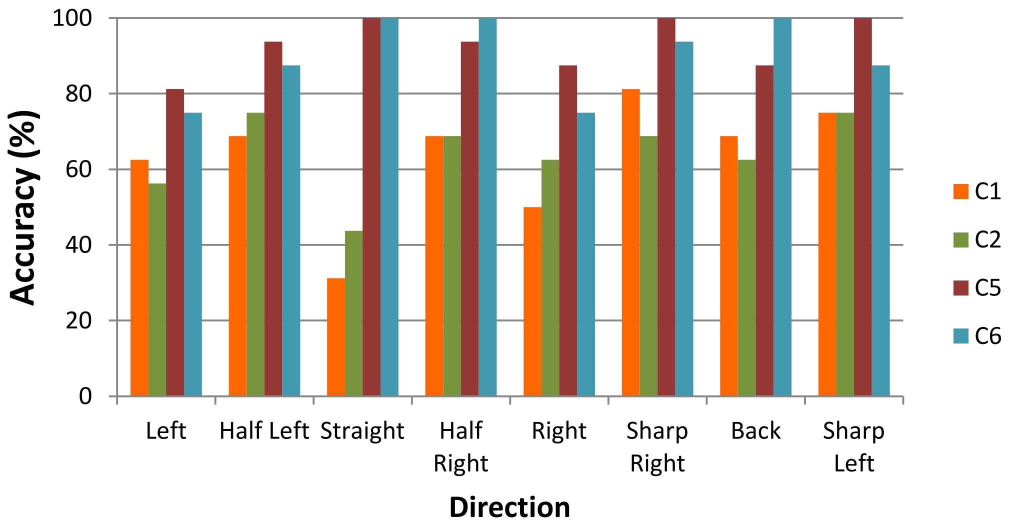

Figure 3.18 Accuracy of responses (%) for all directions with the vertical screen conditions

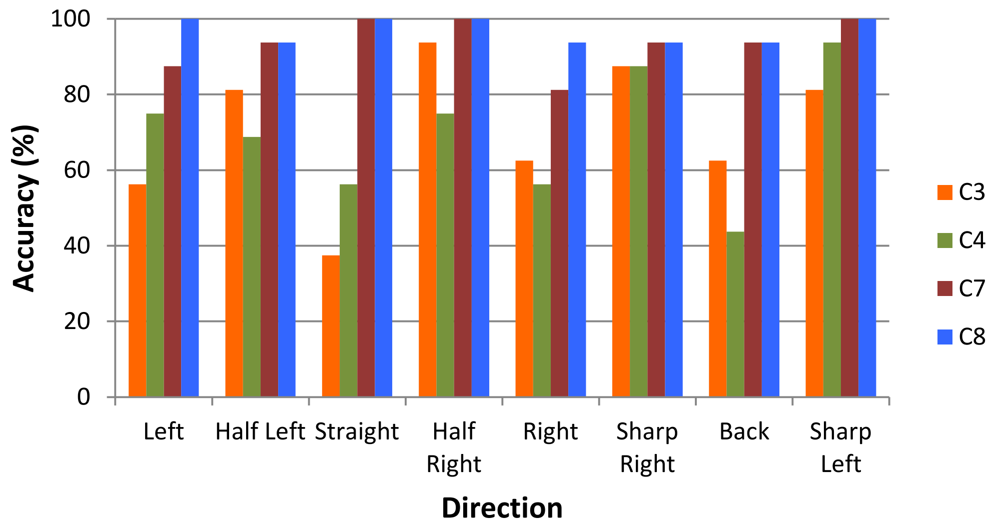

Figure 3.19 Accuracy of responses (%) for all directions with the horizontal screen conditions

In terms of accuracy, the data of the array conditions (C1-C4) were statistically analysed using a one-way repeated-measure ANOVA. The results showed that there was a significant difference in accuracy among different directions, $F(6.05, 380.82) = 5.88$, $p < 0.002$. Post hoc Bonferroni pairwise comparisons showed that accuracy was significantly lower with *straight* than with *half right* ($p < 0.002$), *sharp left* ($p < 0.002$), *sharp right* ($p < 0.002$), and *half left* ($p < 0.05$). There was no significant difference with other direction pairs ($p > 0.05$). In other words, using the array, participants performed worst in accuracy (C1 and C2 in Figure 3.18, and C3 and C4 in Figure 3.19) with vertical (*straight* and *back)* and horizontal saltatory signals (*right* and *left*), which was consistent with the results from experiment 1. The inaccuracy ranged widely from 45 to 180 degrees (both to the left and to the right of intended directions). Also similar to experiment 1's results, they performed faster and more accurately with diagonal saltatory signals (*sharp right*, *sharp left, half right* and *half left,*).

On the other hand, using the belt (C5-C8), there was no significant difference in participants' accuracy with different stimuli, $F(4.94, 311.20) = 1.83$, $p > 0.05$). Namely, participants performed equally well across all directions (C5 and C6 in Figure 3.18 and C7 and C8 in Figure 3.19). Almost all incorrect answers were 45-degree errors.

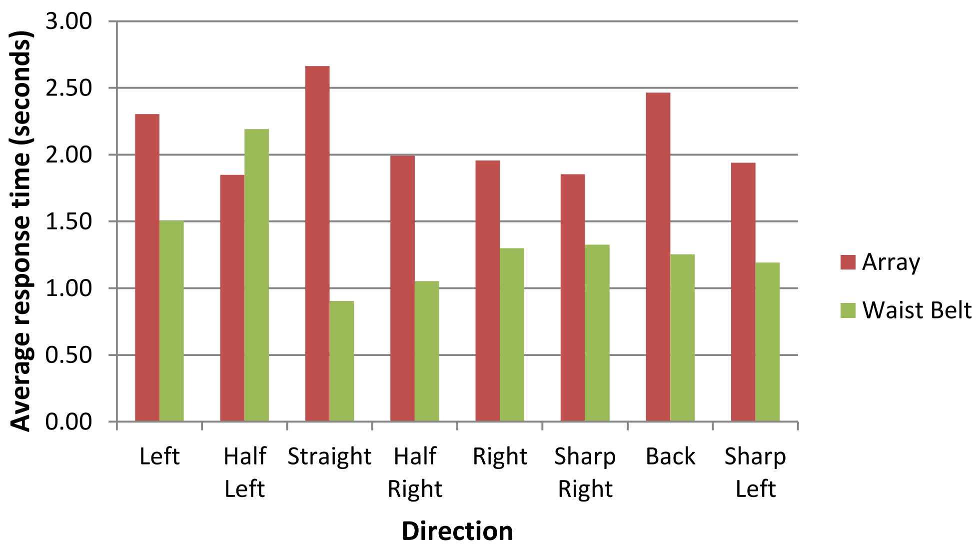

Figure 3.20 Average response time (in seconds) for array conditions (C1 – C4) and belt conditions (C5 – C8)

In terms of time performance, a one-way repeated-measure ANOVA showed no significant difference across array conditions, $F(1.45, 4.36) = 5.51$, $p > 0.05$). On the other hand, there was a significant difference across belt conditions, $F(3.38, 128.26) = 5.21$, $p < 0.05$). Post hoc pairwise comparisons demonstrated that participants responded slower with *half left* compared to *half right*, *straight* and *sharp left* ($p < 0.05$). There was no significant difference with other pairs of directions. However, the time performance in this case is just a fraction of a second which we consider acceptable. The largest difference between mean values of the quickest (0.89 seconds for *straight*) and the slowest (2.14 seconds for *half left*) was only 1.25 seconds. Figure 3.20 demonstrates an average response time for array (C1-C4) and belt (C5-C8). Results confirm that participants responded much slower with the array conditions than the belt conditions on all directions, especially with the *straight* signal. Table 3.10 shows detailed mean response time for all directions across all conditions.

Table 3.10 Detailed Mean Response Time across 8 Conditions

Direction	80 mm Array				Waist Belt			
	Vertical		Horizontal		Vertical		Horizontal	
	Blank (C1)	Map (C2)	Blank (C3)	Map (C4)	Blank (C5)	Map (C6)	Blank (C7)	Map (C8)
Left	2.56	2.13	1.79	2.74	1.57	1.44	1.54	1.47
Half left	1.94	1.48	2.05	1.92	2.02	2.93	1.98	1.83
Straight	3.13	1.88	2.41	3.23	1.05	0.94	0.88	0.75
Half right	1.94	1.66	2.59	1.78	1.09	1	1.28	0.84
Right	2.26	1.7	2.46	1.41	0.97	1.8	1.2	1.23
Sharp right	1.92	1.96	1.56	1.97	1.42	1.94	1.06	0.88
Back	1.67	4.08	2.04	2.07	1.74	1.23	1	1.05
Sharp left	1.67	1.73	1.77	2.59	1.37	1.03	1.29	1.08

Time in seconds.

Other results

Unlike experiment 1 in which we found a positive correlation between body size and performance with the belt, the second experiment showed no significant correlation in any belt condition ($p > 0.05$). Again, unlike experiment 1 in which we found no correlation between body size and performance with the array, experiment 2 found a significant negative correlation in the vertical blank display (C1) ($r = 0.56$, $p < 0.05$) and horizontal guided display conditions (C4) ($r = 0.57$, $p < 0.05$). That is, the smaller the body size, the better the performance with the array.

Overall descriptive statistics showed that males performed slightly better than female participants across the belt conditions with an average accuracy score of 7.57 over 7.33. On the other hand, women were better than men across the array conditions with an average score of 5.92 over 4.71. Across all conditions, women were slightly better than men with an average score of 6.63 per 6.15. However, a Pearson's correlation analysis found no significant correlation between sex and accuracy in all conditions ($p > 0.05$).

Three participants reported physical tiredness on their back after finishing the 4 array conditions. Another three participants wearing the 80 mm array prototype mentioned a high cognitive load because there were many points on their back on which they had to concentrate and work out directions.

With the waist belt, although all participants reported that it was easier to interpret the stimuli, four participants had occasionally looked down at the location of the motors on their body before responding.

Similarly to experiment 1, the waist belt participants had difficulty differentiating directions at their back area, e.g. *back*, *right*, and *sharp right*.

Table 3.11 Mean Scores of Subjective Perception and Interpretation of Tactile Stimuli

	80 mm Array				**Waist Belt**			
	Vertical		**Horizontal**		**Vertical**		**Horizontal**	
	Blank (C1)	**Map (C2)**	**Blank (C3)**	**Map (C4)**	**Blank (C5)**	**Map (C6)**	**Blank (C7)**	**Map (C8)**
Perception	2.19 (0.83)	2.31 (0.79)	2.31 (0.79)	2.25 (0.77)	3.13 (0.72)	3.13 (0.89)	3.13 (0.72)	3.19 (0.75)
Interpretation	1.94 (0.68)	2.00 (0.73)	2.06 (0.77)	2.06 (0.77)	3.50 (0.73)	3.69 (0.87)	3.75 (0.68)	3.75 (0.77)

Scores: n of a 5 point Likert scale, 1 is low, 5 is high. SDs in parentheses.

At the end of the second experiment, participants were asked to rate their *perception* and *interpretation* of the vibration stimuli. Mean scores of subjective *perception* and *interpretation* tactile stimuli for the different prototypes are shown in Table 3.11 (first and second row respectively). These rating values have a strong relationship with users' performance, i.e. the higher the ratings, the higher the performance.

Same as the results in experiment 1, when asked for their preferred wearable interface, all participants preferred the waist belt to the array. Their reasons included: the belt is easy to wear, more flexible than the back array, more comfortable to wear, and provided clear and precise directional information.

Participants indicated no preference between vertical and horizontal screen orientations (i.e. equal preference scores). Although two participants stated that they preferred a vertical screen when wearing the array and a horizontal screen when wearing the belt, both of them performed better with the belt in the vertical screen conditions.

In summary, we rejected both hypotheses (*H2* and *H3*) since the results of experiment 2 showed that participants performed better and quicker with the belt than with the array regardless of screen orientation or visual display type.

3.3.6 Discussion and limitations of lab-based studies

The primary aim of our lab-based experimental evaluations was to directly compare the effectiveness of two established designs of wearable tactile interfaces that have each claimed success in assisting pedestrian navigation. Our results suggest that the array, in either incarnation, was less effective than the belt, with participants unable to quickly and reliably identify directions, especially the vertical saltatory signals (*straight* and *back*). Our findings are consistent with that of a previous study (Tan et al., 2003), which suggested that to improve performance on vertical signals, a '*thick line*' signal (simultaneous activation of all 3 columns on the array) might be used to expand the area of stimulation beyond the neurological gap on participants' backs (see Figure 3.21).

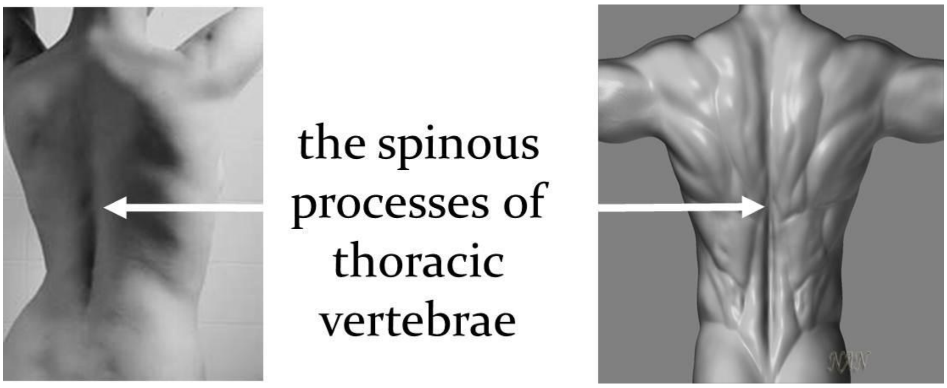

Figure 3.21 Neurological gap on human back. Male participants have a deeper gap in the midline of their back than female participants.

For the degree of error with the array device, it could be caused by the mental workload for signal mapping and interpretation. However, the degree of error was random across conditions in both experiments. Further study is required to identify this issue. With the belt device, there was a degree of systematic error of 45 degrees between the stimulated and the experienced direction. This phenomenon could be explained by Van Erp's (2005) finding that the bias was usually found to be toward the midagittal plane, that is, experienced directions are toward the naval for the front direction and toward the spine for the back side.

Both experiments showed the belt as significantly better than the array across a wide range of conditions. The findings of experiment 2 reassured us that the match between the plane of the stimuli and the plane of responses in experiment 1 did not unduly favor the belt.

Experiment 2 also suggested that the visual display of the directions (in the map conditions) did not aid the perception of and response to the tactile stimuli. Our finding is congruent to that of Karuei et al.'s (2011) that visual workload and loci expectation had no effect on the detection of directions. This offers further support to the notion that a unimodal tactile system, such as the tactile navigation aids presented by Tan et al. (2003) and Van Erp et al. (2005), is feasible without support from other modalities such as visual displays.

During both experiments, we intended not to have participants wearing headphones to block the noise produced by actuators because we would like to observe the usage phenomenon and the effect from other modalities. As we noted in Chapter 2, coherent information across modalities results in sensory augmentation (Turchet et al., 2010). Hence we were sure that the current design would not impede our users' performance. During the experimental sessions, participants wore the devices as they were meant to be worn in practice, i.e. wearing the tactile device whilst other channels were freely available to perceive other stimuli in the environments. Video analysis results revealed that: in the belt conditions, some participants looked at the possible actuators; in the array conditions, some participants used their hands to recall the shape of the line before responding. When asked, none of them reported sound localisation. Our participants were rather related to the vibration cognitively through a glance. We may assume that with vibrotactile sensation, users tend to have made a relationship between what they felt with what they saw rather than with what they heard. These phenomena offer support for MRT theory that our cognitive resources can be used near-simultaneously and effectively performed together given an intuitive display. However, this assumption will require further investigation.

Correlation between body size and performance seemed contradictory between the two experiments. We found a positive correlation between these variables with the belt in the first experiment and a negative correlation between them with the array in the second experiment. This may have resulted from differences in the numbers of petite and large participants in the experiments, i.e. there were more petite participants in the second experiment. An 80 mm array covered quite a lot of their back, perhaps making it easier to distinguish some signals. Even so, the correlation coefficient in these cases was relatively low and reached significance in only two of the eight conditions; therefore findings on this correlation are inconclusive.

Karuei et al. (2011) mentioned that gender has an impact on direction identification performance but the difference is not large. Specifically, males are slightly better at detection and spent a shorter time than female participants. We found that men were slighter better than women but there was no significant difference in terms of performance. This may suggest that tactile displays could help reduce differences in navigation and wayfinding performance in male and female participants (Saucier et al., 2002). However, we did not have equal numbers of both genders so our results cannot be treated as unbiased in this regard. Further studies could explore the effect of tactile communication on the ability to maintain orientation and navigation strategies and the ability to use the strategies in men and women.

From the quantitative results, we conclude that the most important factor that conveyed effective directional information was the direct mapping of motor locations on the body surface to corresponding directions. The layout of the belt wearable device provides this affordance because it provides precise single point stimulation, which is reported to be easily interpreted. Whereas with the array layout, participants reported that they had to memorise start and end points, pay attention on where a signal came from and where it moved; sometimes this caused hesitation, resulting in longer response time and a guessed or skipped answer. In summary, directional information displayed via the belt was perceived as more precise and easier to interpret than that displayed via the back array.

From the qualitative results, users' feedback tells us that all participants in both experiments preferred the waist belt to the array due to factors such as its ease of use, flexibility and comfort level. In addition, the belt provided a directional presentation that was easy to understand and interpret and required no training to achieve high performance.

Overall, the results suggest that the belt is a better choice for wearable tactile interaction than the back array. It is worth noting that our experiments did not seek to tease out which particular features of these two established approaches led to the observed differences. The two approaches actually vary on at least three potentially significant features: physical layout of vibrators, stimuli patterns (tactile flow *vs* absolute point), and body contact areas. We have found no published research that attempts to systematically vary these three features. In the experiments reported here, we have shown that the belt is more effective than the array in the form in which each of these designs has most commonly been realised.

The back array may be useful in some circumstances such as where a tactile display cannot be worn or when it is more appropriate to embed an array into everyday objects such as chairs or car seats. In these cases it may be worth conducting further research to improve the effectiveness of the back array. We did not examine the effects of more extensive training or long-term use. Other studies would be required to investigate these effects, which might help to improve the performance of the back array.

3.3.7 Conclusion of the lab-based experiments

In our study, directional information can be represented straightforwardly by placement of vibrating devices relative either to each other or to parts of the body. This is feasible because this representation requires a small set of discrete values, which can be mapped directly to simple stimuli.

Previous research has shown that two types of wearable tactile displays, a back array and a waist belt, have successfully aided pedestrian navigation. Each has its proponents and each has been reported as successful in experimental trials. However, there is no previous research directly comparing which of the two is more effective and which users might prefer.

In this section, we have reported results from a series of lab-based experimental evaluations, which directly compared the two tactile directional displays in order to address our two research questions:

RQ3: What is the effective form of tactile displays for pedestrian navigation?

RQ4: Which representation technique should be used for direction?

Results indicated that the tactile waist belt with absolute point vibration allowed participants to perform significantly faster and more accurately than the tactile back array with tactile flow vibration.

We did not attempt to isolate and investigate the possible individual effects of vibrator layouts, stimuli patterns or body contact areas that may have contributed to this result. Whether with the belt design or the array design, further research could investigate the effects of alternative instantiations in each of these dimensions. However, this particular concern is out of our current scope of study. Hence, it will be listed in the future work chapter. Future research could also examine the effect of more extensive training on performance and the long-term effects of wearing and using tactile interfaces.

We are aware that the lab-based study is not very realistic for navigation tasks. However, at the stage of the research, our lab-based study tackled abstract questions of vibrotactile interaction, specifically the effectiveness of saltatory cues on an array *vs* absolute cues on a belt. Subsequent work will build on resulting understandings to investigate the application's utility and acceptability with users in the field settings. We explain and discuss such a field evaluation in the next section.

3.4 Field evaluation: testing the tactile directional navigation system in the real urban environment

3.4.1 Overview

Results from the preliminary lab study gave us some confidence that participants would be able to navigate using the tactile belt. We then built a tactile assistive pedestrian navigation system called, TactNav, to be evaluated in the actual urban environment.

The basic concepts of TactNav are as follows:

1. A unimodal tactile display that provides eight egocentric directions (straight, half right, right, sharp right, back, sharp left, left, half left). A straight signal will also be used as confirmation cues; all other directions will also be used as orientation cues;
2. A waist belt with adjustable size and location of actuators to account for users' varying body shapes;
3. Navigation using embedded GPS technology.

As a prototype, our TactNav system was built for functionality and flexibility rather than for convenience or aesthetics of the wearable device. Most of the system components were carried inside a backpack in order to keep the users' hands free.

Whilst recent research (e.g. Bradley & Dunlop, 2005; Ross & Blasch, 2000) has addressed a range of issues concerning navigation for visually impaired users, our TactNav interface was currently designed for only sighted people who may be concurrently involved in other tasks. The two situations have different information requirements, as shown in Chapter 2

Table 2.1 (Bradley & Dunlop, 2005), which suggest that sighted people[38] depend mainly on directional information. Given the minimal information requirement for a sighted and minimally attentive user, a simple interface can be considered. Consequently, our TactNav provided simple directional information via tactile output.

The field study took results of the lab-based study to be evaluated in the urban environment in late 2008. Our goal was to investigate performance with the TactNav system in comparison to another type of existing mobile navigation aid system, specifically a visual map-based navigation system on a mobile phone in urban canyons.

We chose the visual mobile maps because they are widely used. Nevertheless, it has been reported that the small visual display of most mobile GPS units presents users with usability problems caused by, but not limited to, the orientation of displayed maps not being regularly updated to align with the orientation of the user (Goodman et al., 2004). To eliminate this usability problem, we chose the "head-up" maps mode which was reported to be more effective and require less mental effort than the "north-up" maps[39].

Before we can state a hypothesis for the field study, we would like to discuss related work by Duistermaat (2005), Van Erp & Duistermaat (2005), and Elliott et al. (2006). Researchers compared the performance of a tactile-based and a visual-based navigation system in a forested area under conditions of high cognitive & high visual workload (i.e. adding secondary tasks: radio communication and searching for targets) and normal workload. Results demonstrated that under extreme conditions, the tactile version provided better navigation and the secondary task's performance than the visual version. On the other hand, under a normal cognitive load, both systems performed equally well in terms of navigational decision. However, users of the tactile-based system navigated much faster and were able to locate a higher number of obstacles along the route. Additionally, it received higher preference scores than the visual system.

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[38] Visually-impaired users depend on both directional and descriptive information. Should this type of user be our participant, the system is required to provide more types of spatial information.

[39] North-up maps are found to be used in military operations in different types of spaces such as large, infinite or sparse spaces and in the normal pedestrian situation when the movement during a navigation course has paused. In addition, some mobile navigation users prefer north-up maps (Smets et al., 2008).

Our field study was designed to strictly replicate previous experimental studies' settings (i.e. Duistermaat, 2005; Van Erp & Duistermaat, 2005; and Elliott et al., 2006) and apply them to a different type of space. Specifically, we intended to compare both systems in an urban canyon which is considered a large, dense, dynamic space. Walking in an urban context is physically very different from walking in a sparse outdoor environment as in the forest. Factors in the urban context such as city structure, route quality, landmark orientation, types of ongoing activities, and the level of sound and light and other environmental dynamics may constrain a pedestrian's behavior and performance (Millonnig & Schechtner, 2006; Zacharias, 2001; Wang, 2011; Melbin, 1978). However, we cannot necessarily generalise that it requires a higher or lower amount of mental demand in different types of space. With no prior study on the urban environmental effect on navigation performance, we had no grounds to infer the possible outcome other than to anticipate analogous results of previous studies' normal workload outcomes in the urban context.

That is, we considered the testing scenario of a tourist trying to locate an unfamiliar destination as a normal cognitive workload condition. We did not assign a secondary task for such a quest journey.

Based on the original studies, our hypothesis predicted that the different-sensory-based navigation systems would have an effect on time performance. Specifically, navigation time of the tactile-based system would be faster than that of the visual-based system (*H1*).

In summary, we compared our TactNav system with a commercial visual map-based pedestrian navigation application on a mobile phone. We recorded several measures of performance including accuracy (i.e. correctly identified directions) and route completion time.

We were aware that to evaluate mobile guides, percentage preferred walking speed (PPWS)[40] should be measured (Goodman et al., 2004) and we have done so for the field evaluation of TactNav reported in Chapter 5. Nonetheless, for this particular study, we did not use PPWS because the original studies (i.e. Duistermaat, 2005; Van Erp & Duistermaat, 2005; and Elliott et al., 2006) did not measure this value.

---

[40] PPWS is used to measure the extent to which the use of wearable devices is lower than the user's normal walking speed (see Petrie et al., 1998). For more information, see Glossary.

In the next subsections, we reprise research questions to be addressed by the field study. Then, we report results, findings and discuss advantages and disadvantages of the tactile-based and visual-based navigation systems.

3.4.2 Research questions

As we have documented in Chapter 2, that pedestrians are likely to use navigation aids either for quest or exploratory purposes, our first field evaluation will set to test the system with the first scenario (quest) in order to address *RQ5.1 and RQ5.3*.

> *RQ5: What is the tactile navigation system's performance? Specifically,*
>
> > *RQ5.1 Does the system help with different navigation purposes?*
> >
> > *RQ5.3 Is there a problem with the transfer of frames of reference with tactile navigation displays?*

Besides, the visual mobile system can provide some information that the tactile one cannot. That information includes the localisation information which the user is able to refer to with respect to waypoints and other surrounding objects to ensure that one is on the right path. In order to make the TactNav system closely equivalent to the visual one, we have used a straight signal pattern (i.e. vibration on the front motor) that acts as a confirmation cue for the same purpose. All other directions were used as orientation cues whenever was necessary. Then, we tested this signal design in the field trial in order to address RQ4.

> *RQ4: Which representation technique should be used for confirmation and orientation cues?*

3.4.3 Method: equipment, tactile stimuli and participants

Equipment

The tactile-based navigation system: TactNav

We used the same equipment setup of a waist belt as in the lab-based experiments (see Figures 3.5 and 3.7). An additional component was a GPS unit model BT-Q1000, manufactured by QStarz (http://www.qstarz.com/). The GPS unit was connected to the laptop via Bluetooth[41]. Our final system architecture is demonstrated in Figure 3.22.

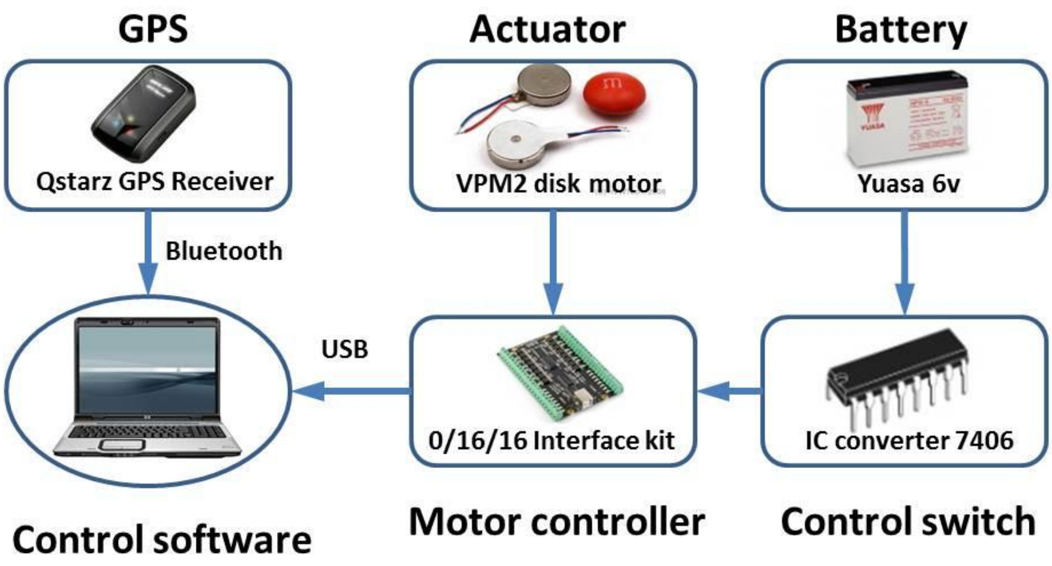

Figure 3.22 TactNav System Architecture

The design of our prototype system was based on an assumption that the route is navigable by establishing sequences of intermediate waypoints and proceeding *forward* in the direction of the next destination on the route. When using a GPS system for navigation, it is crucial that the given directional information is relative to the direction in which the user is heading (Seager & Stanton Fraser, 2007). Our prototype TactNav did not incorporate a digital compass so we had no means of knowing which way the users would be facing during navigation. However, based on our assumption, i.e. given that the user is moving or has recently been moving forward towards a pre-determined destination, we could calculate the direction of motion and give the next waypoint information (during the trials, each participant was accompanied by an investigator so any problem could be dealt with). Such waypoint information was loosely considered as *orientation* cues.

May et al. (2003) reported that sighted pedestrians use structural landmarks to identify a point on the route, and street names to confirm a correct navigation decision. Visual-based navigation systems provided these two types of information whilst tactile-based ones, such as TactNav, would not be able to. To compromise this lack of ability to provide a type of point localisation signal, a vibration on the front actuator, at pre-determined intermediate points between any two turning points (TP) which were far apart, was given as a

[41] Bluetooth is an open wireless protocol for exchanging data over short distances.

confirmation cue in TactNav. The cues were aimed to give the user confidence that he or she was traveling in the right direction towards the next turning point.

The visual-based mobile navigation system: Nokia Maps 2.0™

The apparatus for the visual mobile maps condition was a Nokia N95 handset (Figure 3.23) running Nokia Maps 2.0™ (Nokia Corporation, 2008).

Figure 3.23 Nokia N95, display screen size diagonal 2.6 inches at 240x320 pixels (Courtesy of Nokia Corporation)

Figure 3.24 Examples of the maps displayed in Nokia Maps 2.0 application: Left – a fine granularity of a place with an azimuthal perspective; Middle – a medium granularity of a place with a plan (flat) perspective. Right – a coarse granularity of a place with a plan (flat) perspective. (Courtesy of Nokia Corporation)

The application provided a mapping and navigation service to Nokia's customers. The map system also provided a voice guided alternative. Figure 3.24 demonstrates how the display would look in normal navigation circumstances. The system offers the ability to zoom in and out to see different granularities of the space and a wide variety of azimuthal map projections[42]. Users were able to display different types of spatial information such as direction, landmark and point of interest, distance to destination, speed of movement, travel time and satellite signal strength.

During the field trial, the angular view, and voice guidance were turned off. Other information types except direction were disabled. Navigational logic and assumption in the visual system was set to be the same as in the tactile system.

Stimuli

TactNav

The system was designed to help with quest navigation when a user intends to reach an unfamiliar destination. Generally, the system provided direction information which functioned as waypoint instructions and cues for orientation and confirmation. Additionally, the system also provided a notification when the intended destination was reached.

Stimuli set B was used (see Table 3.2 and Figure 3.11). During the pilot session, our participants reported that simultaneous vibration of all eight motors gave them a very distinct sensation which could be interpreted as an alert. We used this all-vibration signal to indicate "destination reached".

An additional signal pattern for destination is listed in Table 3.12 (please note that signal B3 will be used as a confirmation cue).

Table 3.12 Signal patterns (Number in signal pattern represents motor number in Figure 3.6B)

Stimuli code	Signal type	Signal pattern	Meaning	Actuator's location around the waist
B9	Destination	Synchronised B1 to B8 (in Table 3.2)	Destination reached	All actuators

Prior to the navigation session, the control software was registered with the destination's coordinates then calculated the route. Once navigation started, the system received the user's current position from the GPS unit, constantly compared positioning data with the

[42] Different angular points of perspectives

pre-determined turning points (TP), and activated corresponding actuators as tactile cues at the appropriate turning points.

Results from pilot sessions with four participants helped in determining signal delivery timing. The system calculated the radius of turning points and triggered a set of two vibrotactile signals once participants entered the hot zone (radius of 10 meters). The first signal was given at the defined range (i.e. the edge of the hot zone) and then the second signal was given three seconds later.

Nokia Maps 2.0[TM]

Figure 3.25 Visual stimuli on Nokia Maps

Generally, the mobile map application delivers route guidance instructions by delivering the following 6 types of information (see Figure 3.25 for reference):

- Type 1 — Direction (as a big white arrow)
- Type 2 — Route (in dark grey)
- Type 3 — Your current location if driving (as an arrow at the bottom of the screen)
- Type 4 — Compass (at the bottom left of the screen)
- Type 5 — Information bar (travel speed, distance, and time accordingly)
- Type 6 — Your current position if walking (as a red dot)

We have turned off as many functions and information types as possible in the visual system so that it was closely equivalent to those provided in the tactile system. In the final set up of the mobile map system, information types 1 (direction) and 2 (route) were displayed. Please note that the information bar (type 5) cannot be turned off; instead users were instructed not to pay attention to this information.

For consistency across both types of navigation systems, two types of pin symbols have been used to refer to (1) confirmation cues and (2) destination reached. Please note that both conditions used the same navigation route (with different groups of participants). A confirmation cue appeared as a blue pin on the visual map application at the same points as the confirmation vibrations in TactNav. A visual notification as a white star with a blue flag designated destination reached (see Figure 3.26).

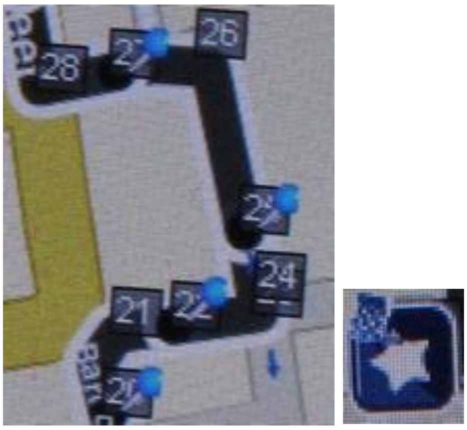

Figure 3.26 Confirmation cues and destination point in the visual mobile map condition; Left – confirmation points, and Right – a symbol for destination reached.

Participants

There were 24 paid participants, 11 males and 13 females with an average age of 29. We adopt the between-group design. Namely, half of the participants performed the mobile maps condition and the other half used the TactNav to navigate the same route. We used independent samples because location-based tasks are particularly sensitive to repetition (Goodman et al., 2004). In other words, if users remembered the route after the first condition, it is likely that this would affect their performance in the second condition. For the tactile-based navigation, none of the 12 participants (six males and six females) had ever used a tactile system. The smallest participant had a 61 cm waist size and the largest 96 cm. Mean waist was 79.17 cm with SD 9.89.

For the visual-based condition, there comprised five males and seven females. 83% of participants had never used a mobile maps application and 92% were not familiar with the particular mobile handset used here.

Figure 3.27 Left – a participant wearing TactNav, Right – a participant using Nokia Maps

3.4.4 Experimental procedures

Participants navigated on foot in an urban setting in the city of Bath where there are a relatively large number of objects and cues in the space. Sessions took place over 10 days. Situations included navigation during weekdays (less busy environment) & the weekend (crowded and noisy environment), and day (bright natural light) & night (dimmer artificial light), clear conditions (clear sky, no wind or rain) & weather conditions (cloudy, windy and light rain).

A pre-determined 1.3km route containing 20 TPs (including the start and end points) was set up (see Appendix 1). Both systems constantly compared the participants' current location (by GPS) with the pre-determined route and triggered an appropriate directional cue (visual or tactile according to the different technologies deployed) at each turning point.

For the tactile condition, the participants were given an explanation of the tactile sensations they could expect and where they would be generated on their skin for each direction. For the visual maps condition, all of the participants were given an explanation of how the mobile application works and what kinds of symbols and icons would be displayed on the screen during the navigation.

For both conditions, as they walked the route shadowed by the experimenter, participants responded to any perceived directional cue by speaking out loud their turn-taking decision according to the direction perceived. Their route and journey duration were automatically logged by the systems. If they took a wrong turn or did not notice the stimulus, the experimenter intervened, giving verbal information about the correct turn and taking note of any incorrect actions.

The tactile condition provided directional, orientation and confirmation cues (the same as a signal to go straight). Similarly, the maps on Nokia were always head-up maps. Direction, orientation and confirmation cues in the visual mobile map condition had only been displayed to participants at exactly the same points as in the tactile condition. For both conditions, there was no overview information provided. Participants were told to omit the other types of information which might be shown on the phone's screen. No other concurrent activity was appointed or allowed during the experimental period.

3.4.5 Results

Performance

Our primary aim for the field evaluation was to investigate the effectiveness of the tactile-based navigation system in a real urban environment for the purpose of quest navigation. In addition, we were interested in comparing our TactNav with an existing commercial mobile assisted navigation technology. We compared a range of performance measures: completion time, walking pace, correct and wrong turns, and missed signals. Correct turns refer to the number of correctly identified directions. Wrong turns suggest the number of incorrectly identified directions. Missed signals reflect the number of times participants failed to notice the stimulus. Results are shown in Table 3.13.

Table 3.13 Mean scores of completion time and walking pace (Time: mins, Pace: km/h, Turns: n of 20, SDs in parentheses)

	TactNav			Visual Mobile Maps		
	Mean	**Min**	**Max**	**Mean**	**Min**	**Max**
Missed signals	0.67 (0.99)	0	3	n/a	n/a	n/a
Correct turns	18.58 (1.17)	17	20	19.08 (0.79)	17	20
Wrong turns	0.75 (0.97)	0	3	0.92 (0.79)	0	3
Completion time	20.4 (1.8)	16.2	22.8	23.2 (0.05)	20.0	30.0
Walking pace	3.9 (0.39)	3.45	4.81	3.39 (0.38)	2.60	3.94

The experimental route was almost traffic free except at one point where the waiting time to cross the street took around 5 - 30 seconds. The waste duration has been subtracted from the overall completion time shown in Table 3.13.

Results indicated that users' performance with the tactile-based navigation was equivalent to that of the visual-based system in terms of accuracy while route completion time was significantly faster with the tactile-based navigation.

With the tactile system, a number of missed signals were reported, i.e. the user did not perceive the tactile stimulus. Independent samples t-tests showed no significant effect of the two systems on correct turns, $t(22) = -1.23$, $p > 0.05$, or on wrong turns, $t(22) = -0.46$, $p > 0.05$. Our results corroborated with those of Elliott et al.'s (2010) indicating participants made waypoint decisions equally accurately in both conditions.

With the visual mobile maps system, the users completed the route with a mean of 23 minutes whilst the system estimated that navigation should take 19 minutes. With the TactNav system, the users completed the route faster, with a mean of 20 minutes. The average walking pace of the TactNav's participants (3.9 km/h) was almost equal to the normal speed of adult pedestrians at 4.2 - 4.4 km/h (Knoblauch et al., 1996). Independent samples t-tests found a significant effect of systems on route completion time, $t(22) = -3.18$, $p < 0.01$, and walking pace, $t(22) = 3.26$, $p < 0.01$. In other words, participants using TactNav moved much more quickly than Nokia Maps' participants. Hence, hypothesis *H1* was accepted.

Pearson's correlation analysis found that accuracy performance was not significantly correlated with sex, $r = -0.37$, and waist size, $r = -0.50$ (all $p > 0.05$).

Other qualitative results

Mean scores of subjective perception and interpretation of maps and tactile stimuli are shown in Table 3.14 (first and second row). Perception refers to how clearly participants felt the tactile stimuli and saw the visual maps. Interpretation refers to the degree to which participants understood the meaning of given tactile and visual information in order to identify directions. Independent samples t-tests found no significant difference on subjective perception scores ($t(22) = -1.43$, $p > 0.05$); participants found that both types of stimuli were equally easily perceived. However, there was a significant difference in the subjective ability to interpret tactile and visual stimuli for direction identification ($t(22) =$

2.16, $p < 0.05$). In other words, users were likely to interpret tactile stimuli more accurately than the visual stimuli.

Table 3.14 Mean scores of subjective perception and interpretation of maps / tactile stimuli, (Scores: n of a 5 point Likert scale, 1 is low, 5 is high). SDs in parentheses.

	TactNav	Visual Mobile Maps
Perception	2.92 (1.00)	3.50 (0.96)
Interpretation	4.00 (0.95)	3.17 (0.90)
Paper-map replacement	4.42 (1.00)	3.33 (1.38)
Paper-map complement	3.50 (1.09)	3.33 (1.23)

We asked participants to rate the scores on which systems could be used to replace or complement paper maps, the most popular medium deployed as a navigation aid. The mean of subjective paper-map replacement and complement scores are shown in Table 3.14 (third and fourth row). In our participants' opinion, either system can be conveniently used to complement paper-based maps ($t(22) = 0.35$, $p > 0.05$). However, the subjective preference for the TactNav system to replace the paper maps was significantly higher than that for the visual mobile application ($t(22) = 2.25$, $p < 0.05$). We assumed that participants found that the TactNav worked quite effectively and that they could benefit from the hand-free and eye-free navigation.

None of the participants reported discomfort with either system. Half of the TactNav users agreed that unimodal tactile output for navigation is a feasible system for real world use. The other half suggested that a combination of tactile and audio communication (e.g. speech) would increase their level of confidence in a non-visual system. An important aspect that should be noted here is that the wearability and aesthetics of tactile systems will be crucial to user acceptance. With a computer in a backpack and a number of visible wires, our current TactNav prototype requires some improvements in that respect.

For the visual mobile maps system, most participants reported a positive experience. Two of the participants suggested that an addition of tactile or audio communication might improve the navigation performance since the concurrent information would help in affirming the decisions to turn and reduce orientation time.

3.4.6 Discussion

The effect of sex and waist size on TactNav's accuracy performance

Results from the field-based study did not indicate any significant correlation between sex & waist size and accuracy performance. The findings on the relationship between gender and accuracy were consistent with lab-based studies. In the field evaluation, we recruited equal numbers of both genders. Hence, the field study's correlation results suggest that the tactile display could help reduce differences in navigation and wayfinding performance between men and women.

For the relationship between performance and the size of the participant's waist, results in both lab-based and field-based studies were inconsistent. At this point, we can only conclude that the significant correlation that was found earlier in two of the eight lab-based conditions may have occurred by chance. Further evaluation to confirm this point is required.

The effect of GPS availability on visual maps orientation and tactile cues temporary absence

Smets et al. (2008) concluded that ease of navigation and task performance with mobile maps are influenced by map alignment to the orientation of the user. We observed the occurrence first hand. The mobile maps application used in our study starts with a north-up map and when the user starts walking it switches to a heading-up map. The device infers user orientation from the recorded direction of travel up to that point. This initial switch took up to 30 seconds and subsequent map rotations suffered from delays. This was due to a combination of satellite signal shortage[43] and the implementation logic of the application, which requires quite a few recorded GPS fixes in order to resolve the heading direction. Therefore, in order to maintain heading-up maps, users often physically rotated the device to match the orientation of the map with the direction of travel. They found it quite difficult to work out the correct orientation but would eventually manage to continue with the journey.

[43] Pedestrians in an urban context are likely to suffer from GPS signal unavailability because the signal could be blocked by surrounded buildings (Wang, 2011).

TactNav's users suffered from the same GPS problem. However, without a screen to look at, users reported getting frustrated and felt lost; some remained idle at the spot while some walked around back and forth to get the signal. Once the GPS signal came through and the system was able to deliver a corresponding cue, they reported that the course of navigation could be continued with minimum effort.

Completion time

All participants using the mobile maps spent time on (1) resolving their current position in physical space by mentally matching the displayed information with actual surrounding landmarks, and (2) reorienting themselves and the device by mapping the displayed information to their heading on the ground. These behaviours occurred across all participants at every turning point regardless of the space's complexity. As noted above, this was due to the map's presentation on the mobile phone not always being promptly aligned with the participants' orientation and heading. This presentation inconsistency caused frequent physical rotation of the phone by participants and longer consideration at each turning point, and required users' mental rotation to align themselves and the maps to the space. All participants suggested that it would be best if the displayed maps always aligned with their heading.

In contrast, participants using the TactNav reported that they had not used any visual or auditory landmarks to navigate. Four participants using the tactile system did spend extra seconds at some turning points waiting for the tactile signal to be presented. This was due to poor performance of the GPS on those occasions. Even so, the completion time and walking pace results suggest that participants performed significantly faster with the TactNav system. We did not measure participants' preferred walking speed (PWS) prior to the experiment (cf. Goodman et al., 2004) but we did attempt to eliminate systematic differences, such as height, between participants in the two conditions.

Both systems at the time of running the experiment (circa 2007) suffered from the same GPS availability problem. Nevertheless, the main factor affecting completion time with the visual mobile maps is the transfer of different frames of reference. With the tactile-based navigation technique, the problem seemed absent.

Problematic part of the route

In both the TactNav and mobile maps conditions, there was a problematic part of the route where there is no vantage point from which the entire space or landmarks can be seen in detail and there are few objects or clues to help in navigation. An aerial view is given in Figure 3.28. Participants were supposed to navigate following the blue line.

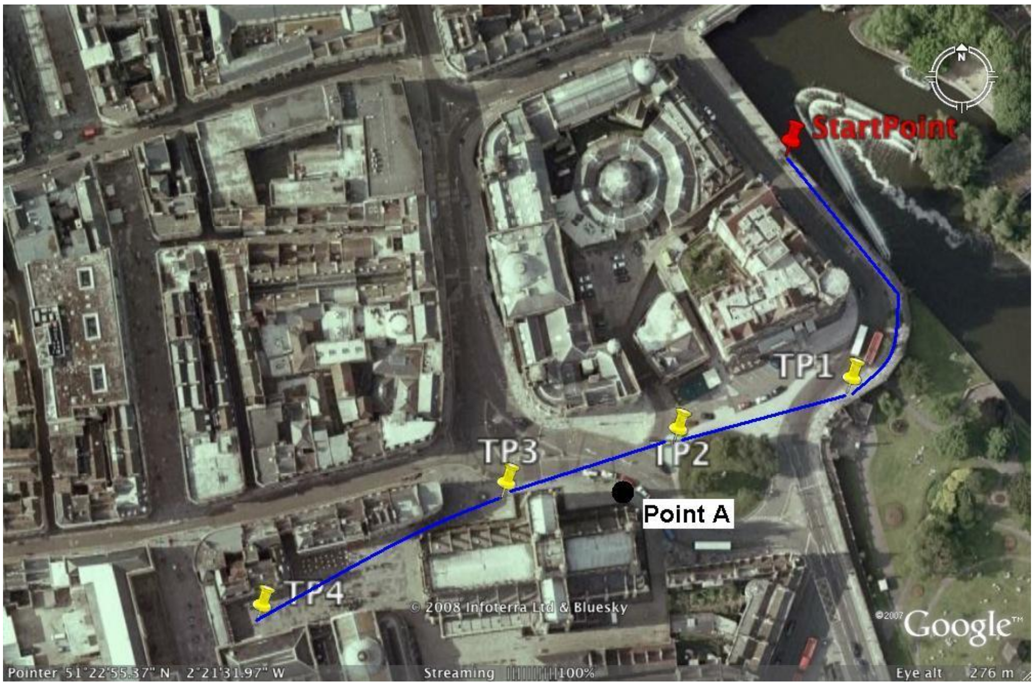

Figure 3.28 Problematic area containing the first four TPs

Figure 3.29 A view at turning point 1 toward turning point 2; holding a phone vertically (i.e. the wrong heading-up orientation)

From TP1 to TP2, most participants in the mobile maps condition held the phone vertically upside down (as in Figure 3.29) and spent a lot of time reorienting themselves and the mobile phone. At this point, the correct orientation of the phone to match the actual space, i.e. to give a heading-up map display, is a horizontal orientation (similar to Figure 3.30).

Since this area has no immediate landmark to refer to, after spending up to three minutes trying to resolve their position, all participants decided to walk straight ahead pending a change of the map display, deferring any decision on changes of direction. In the tactile condition, upon reaching TP1, the front centre motor was triggered. When the participants received the signal, they hesitated in making the decision whether to continue walking along the curved path or to go directly ahead as the stimulus suggested. In the end, all participants made the (correct) decision to go straight ahead (i.e. cross the road to TP2).

Figure 3.30 A view at turning point 2 toward turning point 3; holding a phone diagonally (i.e. the correct heading-up orientation)

Due to the traffic in the area, to navigate from TP 2 to TP 3 all pedestrians had first to cross the road from TP 2 to point A (a black dot in Figure 3.28), then continue walking to TP3. In the tactile condition, the front left motor was triggered indicating the 45 degrees left (half left) direction. 75% of participants made the right decision while 25% turned 90 degrees left. In the mobile maps condition, a correct decision depended heavily on the phone orientation. The correct orientation to give a heading-up display at this point is shown in Figure 3.30. Strongly influenced by the map display on the current orientation of their mobile phone, only 33% of participants in the mobile maps condition made the right choice, while 42% decided to turn right and 25% decided to turn left.

Our findings suggest that tactile-based navigation works better in such a problematic area. This conclusion is similar to that of Van Erp (2002) who reported that tactile-based interaction was successful in a space with few obvious landmarks, such as forested areas.

Cluttered environment

In contrast to the problems mobile map users had in the sparse environment (few objects to refer to), participants also struggled with the mobile maps when the environment was cluttered, either physically or digitally. We consider a physically cluttered space as a space in the real world where (1) the number of objects is so great that it obscures important landmarks or cues; or (2) the number of people is so great that it obstructs navigation flow. Similarly, we refer to a digitally cluttered space as a space displayed on a mobile map where the number of landmark icons and symbols is so great that it overloads users' cognition and blocks a clear view of the map's features and directions. Even though we had switched off the display of touristic icons (e.g. museums, attractions) and navigation information (i.e. compass on the lower left corner), there were some types that could not be switched off such as distance information on the top row and other information such as speed on the bottom row (see Figure 3.25). Almost all participants in the mobile maps condition complained about the information overload on a 4 x 5.5 cm screen but stated that the zoom / scroll functions helped. The most severe problem they encountered was that the navigation direction arrow was so big that it covered street names. In this case, we allowed participants to zoom and scroll to read street names so that they could continue with the journey.

In contrast, participants in the tactile condition had a very simple, uncluttered (tactile) display and reported no problems navigating in a (physically) cluttered environment. Navigation with the TactNav allowed their eyes to remain free for the tasks of scanning the environment and avoiding collisions with other pedestrians and objects in the environment.

Attention

In the tactile condition, participants reported a number of occasions when they did not perceive a signal although the system had generated it. We report these incidents as missed signals in Table 3.13. They may be due to a lack of attention to the navigation system, either because the participants became used to wearing it and no longer noticed it or because of competing demands for their attention in a busy urban environment. Participants in the tactile condition navigated with their eyes free from looking at the system and were found to constantly look at the surroundings. The vibration strength, which seemed to be adequate in the lab, turned out to be rather too weak in the field. We could easily address the optimum level of tactile attention by increasing the signal strength or by giving users control of the signal strength. Our observation is congruent with

Prenav's[44] (Van Erp, 2003/2007; Van Erp et al., 2006) and MRT's[45] (Wickens, 1980) prediction that tactile users could use their free mental resources to perform concurrent tasks effectively.

On the other hand, visual maps' participants were observed looking intently at the phone screen for at least 50% of the navigation duration and frequently manipulating the phone with one or both hands. The high demand on visual attention led to a number of minor accidents during the course of the experiment, e.g. participants tripping over objects or uneven pavements.

Dynamic situation

To navigate with mobile maps, participants needed at least one hand and frequently both hands to manipulate the mobile device constantly whilst mentally reorienting and mapping their position in space. These demands became even more problematic on a windy and rainy day. We had three participants navigate with one hand manipulating a mobile device and another hand holding an umbrella. None of them could conveniently operate the phone using only one hand. Eventually, the evaluator helped by holding the umbrella while they concentrated on navigation. It is perhaps worth noting that we had not intended to run the experiment on a bad weather day. This was one of the uncontrollable factors that normally occur in field evaluation (Goodman et al., 2004).

Confidence in navigation

GPS precision and response time contributed to participants' confidence levels in both the visual and tactile systems. For the visual mobile maps, participants were impressed by the application's response time but were disappointed with the GPS precision. Especially between TP2 and TP3, the mobile maps displayed the current position of all participants incorrectly. This may be due to the nature of the area, which is a churchyard rather than a street or road. The system may have considered this area as inaccessible. For the rest of the route, the current position was not always precise and it required the users to manually update their position (by pressing the handset's '0' button). Once the users pressed it, the position was more accurate but the users lost their zoomed details and had to adjust the display again.

[44] PRENAV emphasizes on automated tasks' performance (see Chapter 2 Section 2.4.1).

[45] MRT focuses on aspects of workload and conflicts (see Chapter 2 Section 2.4.1).

With the tactile navigation, participants were excited by the unfamiliar technology. Nevertheless, unfamiliarity decreased their confidence level. Slow response times, due to poor GPS reception, affected their confidence in the whole system. Since there was no other channel to display current status, participants were left frustrated if there was no tactile stimulus triggered at any turning point. Some participants walked backwards a few meters to try to resolve this problem and continued navigating once they had got the tactile signal.

Bradley & Dunlop (2005) reported that sighted pedestrians use structural landmarks and street names to confirm a decision and gain confidence (see Table 2.1 in Chapter 2). These landmark cues are absent from the tactile system. Although the tactile system was designed to give a vibration on the front motor at pre-determined intermediate points between any two turning points which were far apart, some users reported having less confidence in their heading when the turning points were widely distributed. They suggested that the front actuator vibration should be more frequent.

Subjective feedback regarding the degree to which participants thought the technologies aided their navigation and level of confidence scores for both conditions are shown in Table 3.15. Navigation assistance refers to the degree to which participants thought the system aided their navigation. Confidence refers to the degree to which participants believed that they could rely on the system.

Independent samples t-tests found no significant effect of systems on navigation assistance scores ($t(22) = 1.72$, $p > 0.05$) and confidence scores ($t(22) = 1.30$, $p > 0.05$).

Table 3.15 Mean scores of subjective level of navigation confidence of maps / tactile stimuli, (Scores: n of a 5 point Likert scale, 1 is low, 5 is high). SDs in parentheses.

	TactNav	**Visual Mobile Maps**
Navigation assistance	3.58 (0.79)	2.92 (1.04)
Confidence	3.42 (1.16)	2.83 (0.99)

3.4.7 Conclusion of the field evaluation

In this section, we have reported the results of an empirical study which investigated the use of tactile interaction as a minimal attention interface for assisting quest navigation in an urban environment. TactNav provides a single-point tactile indication of direction. Advantages of the single-point tactile signal include ease of perception and ease of interpretation.

We conducted a preliminary lab-based evaluation to test the effectiveness of the tactile signal design. In our main field evaluation, we compared the performance of our TactNav system with a commercially available visual mobile maps system, Nokia Maps 2.0™. Results showed that the performance accuracy of tactile-based navigation was comparable to that of the visual-based navigation, while TactNav significantly outperformed the mobile maps application in route completion time.

Our study has shown that minimal attention interfaces for specific tasks in the urban environment could be effectively achieved through unimodal tactile output. At this point, we could provide the answer to RQ5.1 (*Does the system help with different navigation purposes?)* that the system can be used for *quest* with acceptable performance.

Nevertheless, subjective data from participants in both conditions suggest that a combination of more than one perceptual channel could achieve better performance, or at least give users higher confidence in the system.

Results demonstrated that participants in the tactile condition did not try to match themselves with any frames of reference during their course of navigation. We conclude that for RQ5.3 (*Is there a problem with the transfer of frames of reference with tactile navigation displays?*), the transfer of frames of references does not seem to exist.

As for RQ4 (*Which representation technique should be used for orientation and confirmation cues?*), our proposed technique seemed to work effectively. Each direction cue served as a waypoint instruction as well as an orientation cue. We provided confirmation cues in the same manner as when we generated the *straight* signal (i.e. vibrating the front centre actuator). Comments from participants on the frequency of confirmation signal generation would be taken into account for future experiment trials.

A useful lesson was that the vibration strength which seemed to be adequate in the lab turned out to be rather too weak in the field. This finding supports Goodman et al's (2004) argument for the benefits of field experiments over lab-based experiments for evaluating mobile systems.

Both the visual and tactile systems could benefit from the addition of a digital compass. The mobile maps system would then not rely on a series of GPS fixes to infer orientation and would be much less prone to the often severely delayed reorientation of the map as the system attempted to maintain a heading-up orientation. The TactNav system would be able to indicate direction more accurately in the event of the user changing orientation with respect to their surroundings.

Our studies have shown that pedestrians could benefit from the nature of touch-based communication to assist them with urban navigation.

3.5 General discussion

Perhaps ironically, the inability of the tactile display to provide overview information benefited the navigation tasks. It completely eliminated previewing the immediate path and consequent attempts at reorienting the display as in the visual condition, resulting in significantly faster completion times. The visual mobile map participants expended considerable time and effort matching the overwhelming amount of information they saw on the mobile screen with the artifacts in the real environment to confirm their route choices. For example, at a turning point with three possible directions to turn, the user of the tactile system would turn left when he or she received a left vibration stimulus, while the user of the visual maps system would typically not turn left immediately even though they saw the big white arrow pointing left on the display. Rather, they would check all the other street names in all the other directions before making the left turn.

Problems with automatic screen orientation, exacerbated by GPS lag, frequently made it necessary to reorient the device and the users themselves. Disadvantages of visual-based navigation included: (1) the inconsistent switching between north-up and head-up map modes led to user confusion; (2) users frequently adjusted a phone’s physical orientation to maintain a heading-up map orientation on the display, leading to longer route completion time; (3) visual-based navigation relies on landmarks such as buildings and street names and it takes considerable time and effort for users to cross-reference these with the displayed map. Nevertheless, a visual navigation aid has the potential benefit to relatively easily provide complex and semantically rich information such as categories of landmarks and street names. Most importantly, electronic visual maps can provide overview information of the space.

With the progress and advancement of future positioning technology[46], some of the problems occurring during our field evaluation may be eliminated and the level of mental workload could be reduced. Nevertheless, we are quite convinced that cognitive workload required by the visual-based system will always be higher than that required by the tactile-based system because of the presence of the demand for the transfer of frames of reference in visual navigation.

Additionally, based on our observation during the field study, we are persuaded that the tactile system suits the nature of mobile users' characteristics (see Chapter 2 Section 2.2) better than the visual one. Navigating in the city, pedestrians require their attentional resources to cope with multitasking, unplanned incidents, and dynamic interaction. Walking with their hand and eye free from constantly looking at the phone would allow them to, for example, take a phone call and carry items such as an umbrella when it is raining. Should these scenarios occur with the mobile map users, they would struggle and their span of attention would be interrupted; they may or may not be able to perform either task effectively. Naturally, if they chose to pick up a phone call, it would require a considerable amount of time to reorient themselves with the system and continue the journey.

With the tactile-based navigation, it is important to note that the tactile signal is brief and skin perception adapts through time. The result of continued stimulation may be a decrease or even a complete elimination of its sensory experience (Schiffman, 1976). This may have occurred in our study, leading to some of the missed signals during the field evaluation.

Nevertheless, tactile-based navigation has benefits that: (1) it is convenient because users do not have to carry the device and can have their hands free for other tasks; (2) tactile communication between the system and the user leaves the user's other senses for other tasks; (3) users who are not good at reading maps or lack orientation and wayfinding skills

[46] As of 2011, positioning technology's users, both pedestrians and vehicular drivers, still suffer from the satellite signals being blocked by buildings (Wang, 2011). The degree of satellite signal unavailability for pedestrians is higher than that for vehicular drivers due to the fact that pedestrians' paths are next to buildings while drivers' routes are further away.

can easily and successfully navigate with touch communication; and (4) tactile communication works under conditions including darkness and very noisy environments since it is a landmark-independent navigation technique.

Disadvantages of our current tactile prototype are: (1) it is somewhat cumbersome to wear; (2) it lacks an automatic re-routing function if a wrong turn is taken; (3) it cannot provide a route overview; (4) it does not provide estimated distance to target points, (5) it does not provide landmark cues**,** undermining participants' confidence in the correctness of their heading between turning points which are far apart; (6) long periods of use may lead to heat-accumulation and muscle fatigue; and (7) as with all vibration-based systems, it is susceptible to not working or not being perceived in high gravity (high G)[47] or vibration environments (Van Erp, 2002).

3.6 Summary

In this chapter, we attempted to answer *RQ3*, *RQ4* and *RQ5*. A series of empirical studies allows us to make a practical contribution. Through the attempts to understand physiology in relation to human perception and information representation issues from literature, we gathered requirements and suggestions for the design of the wearable prototypes. These requirements were then carefully analysed in lab-based evaluations. The findings from lab studies identify the appropriate form of a wearable device and provide the designers with the representation techniques for directional and confirmation information. This contribution is delivered in the form of heuristics for the design of tactile navigation displays: wearability, body sites' sensitivity, suitable direction concepts, the amount of training associated with the use of the display, and a representation technique for the two types of spatial information.

The next step was aimed at improving the effectiveness and efficiency of the system by providing the second most important type of spatial data, landmark (May et al., 2003; Bradley & Dunlop, 2005, Klippel et al., 2009).

[47] High gravity (G) environments refer to the situation when the pull of gravity is significantly greater than normal gravity (i.e. gravity on Earth at sea level). High 'G' situations include, for example, the sudden change in velocity or a very sharp turn at high speed. A rollercoaster offers this high 'G' experience.

Prior to the deployment of landmark information in our tactile-based navigation system, we need to understand the nature of landmarks used in an urban setting. As currently there is no conclusion on the comparative importance of different landmarks or on their use across different navigation contexts, we therefore adopted an empirical approach to identifying landmarks based on people's experiences of journeys involving each of the three navigation purposes (i.e. commute, quest and explore). Such classification of a set of landmarks (*RQ2*) is reported in the next chapter. Following the identification of a minimal set of important landmarks, the next chapter of the thesis will also address tactile representation of landmarks (*RQ4*).

Long is the way, and hard, that out of Hell leads up to light.

(John Milton, 1674)

Chapter 4 An Empirical Investigation into Tactile Landmark Displays

4.1 Introduction

In Chapter 3, we have demonstrated that our prototype allowed users to navigate a city with satisfactory results[48]. Moreover, participants were able to spare their attention to the environments and avoid obstacles along the routes. However, our initial prototype provided only confirmation and directional information. Therefore, the system helped primarily with route guidance rather than with developing spatial knowledge since landmark information was not provided.

As we aimed to improve the system's value, our next phase was to investigate the use of landmarks and their representation in a three-step series of studies. They include (1) selecting appropriate landmarks (a survey study), (2) representing landmarks with tactile signals (a lab study), and (3) deploying a tactile pedestrian navigation system in the real urban environment (a field study). Steps 1 and 2 are reported in this chapter while step 3 is presented in Chapter 5.

Regarding step 1, during the search to find the important type of spatial information, many researchers (e.g. May et al., 2003; Ross et al., 2004; Werner et al., 1997; Werner et al., 2000) have suggested that landmarks are of vital importance. In particular, May et al.'s (2003) study showed that pedestrians use landmarks the most at 72% compared to other types of information in the actual world (road type, junction, distance, street names respectively). However, there is no clarification as to how they are being used across different contexts and navigation purposes because current research on landmarks is subjected to the evaluated locations (Burnett, 1998). We therefore took this opportunity to

[48] Our results were congruented with other researchers' reports of the effective tactile guidance systems for forested areas (Duistermaat, 2005), and urban environments (Frey, 2007; Van Erp, 2005).

empirically classify the use of landmarks in urban environments based on different navigation purposes.

Regarding step 2, we evaluated two tactile landmark representation techniques that could work effectively in combination with the absolute point vibration technique used to represent directions previously shown to be effective in Chapter 3.

To summarise, this chapter is divided into 4 other subsections. The immediate section describes motivations and objectives of both empirical studies. Section 4.3 reports the identification and classification of a set of landmarks or landmark types appropriate for the use of mobile navigation systems in urban contexts. Section 4.4 demonstrates the plan, execution and results of our empirical lab-based study. Finally, the last section summarises the findings of the chapter, provides a limited list of landmarks and concludes with the chosen representation technique for landmarks which would be used in the field-based evaluation of the system (i.e. step 3 of the series).

4.2 Motivation and objectives

4.2.1 A user survey study on important landmarks for pedestrian navigation in urban environments

The motivation for the survey study builds upon a limited list of information requirements for pedestrian navigation derived from the literature in Chapter 2. In pedestrian navigation research, the top two information types that pedestrians use are: directions and landmarks (Bradley et al., 2005; May et al., 2003). Directional information is crucial to the success and performance of navigation (i.e. providing guidance to destinations). Landmarks are navigation cues that help construct *route*[49] (paths between locations) and *survey*[50] (relationships amongst locations and paths) knowledge which in turn builds cognitive representations of the surroundings, i.e. spatial knowledge.

We have found that none of the landmarks studies ranked them by their usage popularity according to different navigation purposes. We assumed that the reason behind the

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[49] Route knowledge is organised in a human's mind and being accessed sequentially as an ordered list of different locations with an egocentric perspective (Werner et al., 2000).

[50] Survey knowledge is an integrated form of spatial locations and their relationships. It is organised in a global, exocentric outlook, i.e. geographical coordinates (Werner et al., 2000).

absence of such a study is that it is difficult to define good landmarks beforehand or without visually analyzing the to-be-navigated area. In addition, it is not practical to generalise them from a single location study because landmarks could be highly varied from one location to another. As a result, visual navigation systems offer a large number of possible landmark categories (e.g. Millonig & Schechtner, 2005; Nokia Maps™ 2.0; Nokia Maps™ 3.0; Garmin Nüvi™).

The focus of our empirical study is to identify and classify landmarks used with urban contexts for three navigation purposes, suggested by Sorrows & Hirtle (1999) and Allen (1999), namely commuting, questing and exploring. We have two main objectives in carrying out this empirical study on landmark usage. First, we would like to inform the design and use of the increasingly widespread visual navigation aids on mobile devices. Existing navigation systems typically present large lists of landmarks, some of which are not necessary. It could be more efficient and effective to present only a minimal number of landmarks that have been identified as most useful for particular navigation purposes. Secondly, we expected that the limited list of seven landmarks would be useful for the development of tactile mobile navigation aids, an area that has so far seen some research but no successful commercialisation. Specifically, the list would be used as a basis in the tactile landmark representation study.

4.2.2 A lab-based comparison experiment: Comparing two vibration techniques for landmark representation

Tactile directional representation has been widely studied and tested but there is no published study attempting to represent landmarks with tactile signal.

As we aimed to develop a tactile navigation display that can provide directional and landmark information, the chosen techniques to represent landmarks must work effectively and be distinguishable from a tactile technique used to represent directions that has been demonstrated in Chapter 3. This challenge entails controlling signal salience and perception capacity (MacLean, 2008b). We had two main objectives in carrying out this lab-based empirical study: (1) investigating tactile representation techniques for landmarks and (2) investigating human cognitive capacity for spatial information when both direction and landmark signals were presented. We were interested in the effect of presenting both information types on human perception, specifically in terms of learnability, distinguishability, memorability, performance and preference.

4.3 A user study on important landmarks for pedestrian navigation in urban environments

4.3.1 Overview

In both tactile and landmark research domains, researchers (Golledge, 1999; Klatzky & Lederman, 2002; Brown et al., 2005; Chan et al., 2005; Gallace et al., 2006; Millonig & Schechtner, 2005) reported that the thresholds of tactile patterns and number of landmarks, which humans can remember and distinguish, are 4-7 patterns (the lower the better), because human memory is limited and tactile communication requires training. These findings suggest an upper bound on the number of landmarks it may be useful to represent within a given navigation task and context. Given such constraint, it is important to identify which small set of landmarks is most likely to be useful because most commercial systems currently provide very large sets, each containing approximately 40-50 landmark categories (see Appendix 2.1 Table A2.2 for more detail).

Several lists of 'most used' landmarks have been reported by researchers (Baus et al., 2007; Grabler et al., 2008) (See Appendix 2.1 Table A2.1). Nevertheless, restricted locations did not provide adequate data for a generalisation of a set of landmarks.

Alternatively, the identification of reliable landmarks could be achieved using several data analysis and mining techniques (see Raubal & Winter, 2002[51]; Grabler et al., 2008[52]). However, these techniques do not account for differences in the visibility of objects depending on the direction from which they are viewed (Brenner & Elias, 2003; Millonig & Schechtner, 2005). Furthermore, these techniques only focused on landmarks surrounding decision points while studies revealed that landmarks along the route help improve many aspects of navigation; for example, increasing users' confidence and decreasing navigational error (Ross et al., 2004). Hence, using such automatic capturing techniques may not provide a practical list of landmarks for different navigation purposes in real use.

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[51] Landmarks were captured automatically from existing spatial databases by using techniques such as an analysis of visual attraction of facades adjacent to decision points (Raubal & Winter, 2002).

[52] Grabler et al. (2008) analysed attribute values of spatial data records such as buildings' shape/label and usage types and ranks these attribute values in order to identify the most suitable landmark at each decision point.

Therefore, to achieve our objectives for the first step in the series of landmark studies, we adopted an empirical approach to identifying consistently used landmarks based on people's experiences of journeys involving each of the three navigation purposes. Our chosen techniques were a questionnaire study targeting worldwide respondents as well as *in situ* face-to-face interviews with foreign and local pedestrians in the city of Bath, United Kingdom.

4.3.2 Research questions

For this particular step of the study, we seek to answer the following research question:

RQ2: How do pedestrians use landmarks for different navigation purposes?

Specifically, we were looking for answers to the following specific questions:

RQ2.1 Do pedestrians use landmarks differently for the 3 different navigational purposes of commuting, questing and exploring?

RQ2.2 When do pedestrians use landmarks during navigation?

RQ2.3 What are the most important landmarks for each navigation purpose?

4.3.3 Method: participants and choices of landmarks

Given the requirement to question participants worldwide, an online survey was an appropriate approach for this study. However, online surveys can be limited by their lack of direct interaction between an interviewer and interviewees; therefore, we also conducted face-to-face interviews *in situ* with participants who had just been engaged in an urban pedestrian journey. We intended that the results from the online and face-to-face surveys would complement each other.

Participants and their geographical locations

Online participants were recruited by convenience sampling whilst face-to-face participants were approached randomly and recruited according to their different navigation purposes. We interviewed tourists for questing and exploring purposes and local residents for the commuting purpose. From the online participants, we collected 100 complete responses from different geographic locations[53] (see Table 4.1). There were 40 men and 60 women, mean age 39 (SD=8.4, range 18–60 years old). We conducted 60 face-to-face interviews in the city of Bath, UK with 32 men and 28 women, mean age 36.2 (SD=7.95, range 18-40 years old).

For online participants, 76% (commuting), 23% (questing) and 5% (exploring) of respondents had made the reported journey within the week prior to the study. 86% (commuting), 64% (questing) and 26% (exploring) had made it within 1 month. If the journey reported by an online participant was over a year ago, we discarded their data as unreliable. All face-to-face participants made their reported journey immediately before their interview.

Table 4.1 Percentages of Online Answers by Continents

Continent	% of Responses	Countries of Origin
Asia	61	Thailand, Korea, Japan, China, India, Singapore, Malaysia, Cambodia, Dubai, and Vietnam
Europe	33	UK, Italy, Spain, France, Germany, Ireland, The Netherlands, Iceland, Poland, and Portugal
North America	5	USA and Canada
Australia	1	Australia

For online responses, we were aware that there are probable differences in land use in the different geographical locations. According to the routes described by our online participants, these urban spaces are similar with respect to the key characteristics we are

[53] The full list of cities: Aachen (Germany), Amsterdam (The Netherlands), Barcelona (Spain), Bangkok (Thailand), Bath (UK), Bournemouth (UK), Bristol (UK), Cambridge (UK), Chiba (Japan), Cordoba (Spain), Dubai (), Dublin (Ireland), Durham (UK), Florence (Italy), Florida (U.S.A.), Glasgow (UK), Granada (Spain), Krakow (Poland), Leeds (UK), London (UK), Lyon (France), Funchal (Madeira, Portugal), Lamphun (Thailand), Madrid (Spain), Manchester (UK), Milan (Italy), Napoli (Italy), New Orleans (U.S.A.), Osaka (Japan), Oxford (UK), Paris (France), Phuket (Thailand), Pisa (Italy), Porto (Portugal), Rayong (Thailand), Reykjavik (Iceland), Rome (Italy), San Diego (U.S.A.), San Francisco (U.S.A.), Singapore, Tokyo (Japan), Torino (Italy), Toronto (Canada), andWollongong (NSW, Australia).

interested in for our purposes here. That is, they can be considered as *large*, *dense*[54] and *cluttered*[55].

The face-to-face interviews were conducted in the city of Bath, United Kingdom. The city is relatively small, with an area of 11 square miles (28 km^2). The population of the city is approximately 100,000 inhabitants (as of 2009, the time of the study). It is a major tourist centre of the region with over one million staying visitors and 3.8 million day visitors per year (B&NES council, 2008). The city centre where the interviews were conducted is dense and cluttered.

Choices of landmarks

We gathered lists of landmarks from several lists published in research papers (e.g. Burnett, 1998) as well as ones provided in commercial pedestrian navigation systems (e.g. Nokia Maps™ 2.0). We, then, compared and combined them resulting in a new collection of 50 landmark categories (see Appendix 2.1).

4.3.4 Procedures and rating scales

Procedures

For the online version, participants were asked to think about actual journeys they had made for each navigational purpose and describe landmarks they used in those journeys together with the landmarks' importance for that particular journey. Each participant answered three parts of the questionnaire, corresponding to questions about using landmarks in pedestrian navigation for three purposes: *commuting*, *questing* and *exploring*.

For each journey with a particular navigation purpose, each participant first identified: (1) a navigated area, (2) if they used landmarks, and (3) if such landmarks were in the physical space or they used landmarks on any guidance system, e.g. a map. After that, they rated each of the 50 landmarks in our set by their importance as navigational aids for the journey on a 5-point scale, 1 being 'not of use', 2 being 'use, not important' and 5 being 'use, very important'. We also collected data on the timing of their use of each landmark. Following

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[54] Dense space is one where there are relatively large numbers of objects and cues in the space (Carter & Fourney, 2005).

[55] In cluttered space, the number of objects is so great that it may obscure important landmarks or cues (Carter & Fourney, 2005).

May et al. (2003), we presented three choices of usage timing: before decision points, between points on the route, and both. Participants were given opportunities to specify other kinds of landmarks used that were not included in our set.

In the face-to-face interviews, each participant first identified which of the 3 purposes they had just been engaged in and then answered the questions only with respect to that purpose of navigation.

Rating scales

Responses from both online and face-to-face survey were used to calculate three rating scales: frequency (F), importance (I) and ranking (R) scores.

The frequency score (F) is the number of times each landmark was used across responders for a particular navigational purpose.

Frequency score = Σ (landmark usage frequency)

For example, for the explore purpose, if the landmark type *tourist attraction* was used 41 times, its frequency score is 41.

Importance score (I) is a summation of weighted importance scores of each landmark across responders.

*Importance score =Σ ((Σ (not important rating) * 1) , (Σ (slightly important rating) * 2) , (Σ (important rating) * 3) , (Σ (very important rating) * 4))*

For example, if the landmark type *tourist attraction* has received scores of 2, 8, 11, and 20 for it being (1) used but not important, (2) slightly important, (3) important and (4) very important accordingly, its importance score is (2*1) + (8*2) + (11*3) + (20*4) = 131.

A ranking score (R) is a summation of weighted ranked scores of each landmark across all respondents. For this particular rating, participants subjectively chose seven important landmarks, regardless of the area they were navigating.

*Ranking score = Σ ((Rank1*7) , ((Rank2*6) , (Rank3*5) , (Rank4*4) , (Rank5*3) , (Rank6*2) , (Rank7*1))*

For example, if there were 8, 7, 7, 1, 2, 1 and 0 respondents that gave a rank of 7 to 1 respectively to the landmark type *tourist attraction*, its ranking score equals (8*7) + (7*6) + (7*5) + (1*4) + (2*3) + (1*2) + (0*1) = 145.

4.3.5 Results

The minimal set of important landmarks

Table 4.2 shows top ranked landmarks in descending order of scores (see Appendix 2.3 for detailed rating scores). Based on the overall ratings by both online and face-to-face participants, there are a few common landmarks that pedestrians use as cues to aid their navigation across all three navigation purposes. Results suggest that the most important landmark is *mall and market* since it scores highly in all but one of the cells (i.e. the commuting purpose in the city in which we ran the interview sessions).

Table 4.2 Side-by-Side Comparison of Top Ranked Landmarks (in descending order of scores)

Purpose	Top Landmarks (Global Rating)	Top Landmarks (Global Ranking)	Top Landmarks (of the city of Bath)
Commute	Mall and Market Traffic light Public transport Bridge Financial service	Well-known shops / business Mall and Market Traffic light Public transport ATM Educational institute Bridge	Monument and Memorial
Quest	Mall and Market Bridge Railway stations Tourist attraction Religious place Traffic light Restaurant	Mall and Market Well-known shops / business Bridge Tourist attraction Hotels Religious place Restaurant	Mall and Market Public transport River Religious place Bar and Pub Railway Station Monument and Memorial
Explore	Tourist attraction Hotels Mall and Market Bridge Monument and Memorial Religious place Public transport	Tourist attraction Hotels Mall and Market Other unique landmarks Monument and Memorial Railway station Religious place	Tourist attraction Railway station Mall and Market Monument and Memorial River Public transport Religious place

Nonetheless, these top-ranked landmark categories might not be generalisable due to different morphologies of the surveyed cities. Religious places provide a good example. Some cities contain hundreds of landmarks of this category, e.g. temples in Bangkok, that are highly visible and distinct from their environments, hence their high frequency of use as landmarks by our respondents. On the other hand, some other cities, e.g. London, contain hundreds of local churches which are not visually or structurally salient (cf. Klippel & Winter, 2005). As a result, pedestrians did not select such landmark categories as cues for navigation in those cities.

The *other unique landmark* category is frequently used in navigation but is not generalisable. This category includes symbolic or iconic landmarks of a given city or famous chain stores that are located in strategic areas or at important decision points on the route. Symbolic landmarks may be instances of the generic landmark categories, e.g. tourist attractions. Famous chain stores could also be instances of more generic landmarks, e.g. restaurants. Further work would be required to enable a mobile navigation aid to determine such examples in advance of use. One potential approach may be to employ field assessment of each city for such landmarks (Burnett, 2001).

The highest scoring landmarks for each navigation purpose were those that are part of the urban infrastructure rather than natural landmarks. These high scoring landmarks, by their design although not necessarily by intention, possess the characteristics of good landmarks and their types and locations are useful as navigation cues for each purpose.

We can see from the variability of participants' ratings that the value of landmarks varies from one situation to another. For example, *tourist attractions* offered little assistance to a quest journey while they were the main, if not sole, purpose of exploring. According to Sorrows & Hirtle (1999), different types (i.e. semantic, visual and structural types) of landmarks are used for different navigational purposes. Our findings here suggest that the same landmark may be used for different navigational purposes to a greater or lesser extent.

It is worth noting that continuous objects, such as a river, were identified in our face-to-face interviews as crucial to navigation. While a visual navigation aid can readily represent such features, an auditory or tactile pedestrian navigation guide would struggle to indicate such landmarks clearly, more so even than the other kinds of landmarks considered. This issue will require further investigation to clarify its potential for real world use.

Qualitative data and other results

Qualitative data from the face-to-face interviews revealed several interesting navigation patterns:

- For exploration, pedestrians generally have an intention to visit some culturally important landmarks. These landmarks serve as their destinations. Nevertheless, they have little idea what generic landmarks they would use to aid their navigation to reach such destinations. Hence, they decided not to use landmarks as navigation cues or confirmation that they were on the right path. Instead, to reach destination landmarks, they relied on directional and textual information (e.g. street names).

- Some explorers navigated blindly by following another explorer (e.g. a friend who excels in navigation). These pedestrians were not able to remember any landmarks along the route except destination landmarks. Although they remembered these destination landmarks, they were not able to associate their locations with the whole route.

- About 60% of explorers who used maps tended to use them continuously throughout their journey and depended entirely on them.

- Most of the “questers” stated that they would first study the route and try to memorise directions and landmarks leading to the destination. Once they embarked on the journey, they would try to recall the route and associate landmarks seen in physical space with landmarks in their memory.

Results from both the online survey and face-to-face interviews also suggest the following:

- Commuters made little use of landmarks but may use a few important landmarks for navigational choices, particularly in homogeneous urban environments.

- From the online survey, the average number of landmarks used per journey for different navigation purposes was as follows: 6.5 (commuting), 12.47 (questing), and 11.04 (exploring). From the face-to-face interviews, the average number of landmarks was: 1 (commuting), 4.42 (questing) and 10.4 (exploring). Based on routes taken by each interviewee, we found that factors influencing these numbers include: differences in length of journey (i.e. a quest is normally shorter than an exploratory journey); and differences in the number of destinations (i.e. a quest normally involves one destination while an exploration involves one or many destinations).

- The number of landmarks used per journey for the quest and exploratory purposes may vary depending on the nature of routes and areas. For example, some large cities contain a wide range of different landmarks that may be distant from each other, while other smaller urban areas contain few landmark categories that are more proximally located in the immediate vicinity. To identify factors influencing these patterns, further study is required.

- All responders across all navigational purposes stated that they have used landmarks both before decision points (to make navigational choices) and along the route (to confirm navigational decisions). These findings are congruent with previous research (e.g. Michon & Denis, 2001; May et al., 2003). Interestingly, most of the landmarks used for commute and quest purposes are located near decision points whilst landmarks used for explore can be both near decision points and scattered along the route.

For the descriptive analysis of responses on landmark's importance and usage from both online and face-to-face respondents, see Appendix 2.2.

4.3.6 Limitations of the study

In order to collect descriptive data from large samples, we decided to carry out a survey research using both questionnaires and interviews. Hence, the study presented in this section is based on subjective ratings as opposed to field study observations. Advantages of this environment independent setting technique include ease of conduct and relatively low cost (Kjeldskov & Graham, 2003). However, we were aware that using surveys, data collected may be incomplete or unreliable because respondents: being reluctant to answer; not remembering details of their journeys; trying too hard to be helpful or to look smart; or just simply because they were too busy that they did not carefully answer the questionnaires.

In addition to the above potential flaws, there were several limitations as follows:

- Sample subjects of questionnaires were not entirely random. They were among highly graduated peers and middle class population who use English as their first or second language. Consequently, results reported here may suffer from sample bias.
- The set of landmarks provided in our questionnaires was derived from several previous studies, which categorised them subjectively based on participants'

responses on landmark usage and characteristics. Hence, we are faced with mixed levels of landmark abstraction.

- There is no concrete measurement of variability in our respondents' spatial abilities that might contribute to the results.
- The location for face-to-face interviews did not contain all 50 landmarks in our reference set. Thus, results from the face-to-face sessions could be biased since some landmarks could never be chosen.
- There were an unbalanced proportion of answers from the online survey (61% from Asia and 33% from Europe). The face-to-face interview sessions were in a European city. While interviewing in a single city reduces the generalisability of the interview results, it facilitates comparison across individual respondents in one specific locale where we expect to conduct further work, and provides some complementarity to the more distributed, and more Asian, online survey results.

4.3.7 Conclusion

Despite the abovementioned limitations, we believed that this survey study has yielded meaningful results on how people generally use landmarks in different urban areas. The landmark study's findings could be useful for designers in suggesting contextually prioritised landmarks for any-sensory-based navigation applications.

The survey results would be used to address *RQ2* as well as to form a basis for our next study.

In response to *RQ2.1 Do pedestrians use landmarks differently for the 3 different navigational purposes of commuting, questing and exploring?*, our survey suggests that pedestrians with different navigation purposes use slightly different sets of landmarks while different cities have different culturally unique landmarks. Landmarks are very important for questing and exploration purposes. There are common important landmarks like malls and markets, and religious places, bridges, and railway stations in cities across the globe. The importance of other types of landmarks as navigation cues is influenced by both the specific morphologies of the cities and the navigation purposes. Each city usually has at least one unique 'other' landmark which is called by its unique name rather than being subsumed in a landmark category.

Usage patterns are also different for different navigation purposes. The number of landmarks used and frequency of use are very low for commuting, with the vast majority of commuters not using them at all. Pedestrians use more landmarks and more frequently for questing and exploring purposes. For these two purposes, participants described different information processing models. With questing, which refers to traveling from a starting point to an unfamiliar destination, most people would try to look at the map and memorise the route and landmarks before they embarked on their journey. On the other hand, explorers continuously matched landmarks on maps with landmarks in physical spaces throughout the course of navigation.

With respect to *RQ2.2 When do pedestrians use landmarks during navigation?* all our participants across all 3 navigational purposes stated that they used landmarks both before decision points (to make navigational choices) and along the route (to confirm navigational decisions). These findings are consistent with previous research (e.g. May et al., 2003; Lovelace et al., 1999; Michon & Denis, 2001). Results from our study informed that most landmarks used, if any, for commuting and questing purposes were located near decision points while landmarks used for exploring were distributed along the path of travel.

In response to *RQ2.3 What are the most important landmarks for each navigation purpose?* we have demonstrated the most important landmarks for different navigation purposes in Table 4.2 (for detailed rating scores, see Appendix 2.3).

4.4 A lab-based comparison experiment: Comparing two vibration techniques for landmark representation

4.4.1 Overview

Following the identification of a minimal set of important landmarks, the next step is to investigate their tactile representation.

At this particular point in the research program, we needed to carefully choose appropriate representation techniques that make one spatial information type distinguishable from another. Namely, the representation techniques were required to afford learnability and differentiability among tactically represented *landmark* signals themselves as well as with the *direction* signals. The designed signals should not only allow the user to distinguish different sensations but also recognise the meaning of those various signals being emulated (Sharp et al., 2007; 2011).

According to suggestions, there are two approaches in such representations, either to use metaphorically developed symbols (i.e. symbolic mapping) or arbitrarily assign associations of chosen signal patterns and their meaning (i.e. abstract mapping) (MacLean, 2008).

The abstract approach focuses on manipulating a stimulus' characteristics such as frequency and waveform. The mapping involves the arbitrary association of a set of data to their manipulated vibration signals. A few examples of the abstract approach exist in studies of signal differentiability & recognition (MacLean & Enriquez, 2003; Brown et al., 2005; Van Erp & Spapé, 2003; Ternes & MacLean, 2008) and meaning recognition (Enriquez et al., 2006). Results from these studies informed researchers about determining factors for differentiability such as *frequency* (MacLean & Enriquez, 2003) and *evenness* (Ternes & MacLean, 2008), but not about meaning association.

Unlike the abstract approach, symbolic mapping is the mapping of a limited set of data to their symbolically associated vibration signals, i.e. semantic association of stimuli with known metaphors. For example, Chan et al. (2005) designed a symbolic tactile set in which signal patterns were associated with heartbeat and finger-tapping metaphors. The heartbeat metaphor was used to indicate the urgency situation (slow – fast); the finger-tapping was used to indicate the 'waiting' status.

If we were to map landmarks using a symbolic approach, appropriate metaphors would require investigation. For example, it might be possible to draw on a shape metaphor, with each landmark signal represented by a simplified form of its shape. However, such an approach would require a different hardware layout, number of actuators and actuator placement (e.g. Bach-y-Rita et al., 1998) from the waist belt approach adopted in this research. In addition, the numerous landmarks studied in research projects and used in commercial systems are not systematically classified, are highly diverse and are often poorly differentiated. Unlike a discrete set of directions, a landmark data set could be large and arbitrary. As a result, signal patterns for landmarks and their meaning associations are effectively arbitrary. All these constraints suggest an abstract approach to extending our tactile directional representation technique to include the tactile representation of landmarks. Nevertheless, this abstract approach requires users to memorise and understand vibration patterns and their associations and later recall them. Perception of these arbitrary signals is expected to be gained through explicit learning (Garzonis et al., 2009). In other words, we asked users to use their sense in a manner that does not happen naturally. In a way, an abstract mapping approach introduced an entirely different concept of landmark representation from that of directions.

As there was no reported study that attempted to provide information presenting different approaches, we took the opportunity to evaluate and compare the following two abstract alternatives.

To create a distinguishable and learnable set of abstract tactile stimuli, researchers (Chan et al., 2005; Van Erp & Spapé, 2003; MacLean & Enriquez, 2003; Tan et al., 2003; Brown et al., 2005; Enriquez et al., 2006; Ternes & MacLean, 2008) have manipulated stimuli's frequency, amplitude, waveform and rhythm. Results suggested those tactile signals' physical characteristics such as *frequency (*MacLean & Enriquez, 2003)*, tempo* (Van Erp & Spapé, 2003) *and note length* (Ternes & MacLean, 2008) as well as signal's qualitative characteristics like *level of intrusiveness* (Van Erp & Spapé, 2003) and *evenness* (Ternes & MacLean, 2008) were primary to tactile signals' distinguishability. We decided that the latter two qualitative characteristics are too intangible and not clearly described. The analysis of the abovementioned related work has suggested that a technique of manipulation of tactile signal duration (i.e. note length & tempo) on a single actuator to create a variety of rhythms provides effective results. Consequently, we chose the heuristic tactile rhythms proposed by Ternes & MacLean (2008) as the first assessed alternative of this comparative study. The stimuli set contain 21 signals; the set will be discussed in more detail in Section 4.4.5.

Another abstract technique that may help the users of a tactile navigation system distinguish direction from landmark signals is to introduce *discontinuity*. Having motivated our objective of investigating representations of direction and landmark type with the waist belt, a technique to introduce discontinuity had to be localised to the waist area. Since any directional signal is generated on one actuator, discontinuity may be achieved by increasing the number of contact points on the body (Schiffman, 1976), e.g. using a combination of two or more actuators (Loomis & Lederman, 1986). Although proposed, this technique has not previously been investigated; therefore, in this study we examined the use of two actuators to create unique tactile stimuli as the 2nd assessed alternative.

The design challenges also include the creation of a usable set of tactile icons to be displayed on a device when rendering size is limited (MacLean, 2008) and human tactile perception capacity is restricted (Schiffman, 1976). An approach to the tactile representation of landmarks therefore requires two steps: the identification of a limited set of appropriate landmarks and the selection of appropriate representation techniques. The number of unique landmarks that could be represented is very large but both Chan et al. (2005) and Gallace et al. (2006a) have suggested that the optimum number is seven. In the previous section, we identified small sets of seven important and generalisable landmark types for different navigation purposes. We use the set of Bath's top landmarks here (see Table 4.2). Specifically, landmarks used in this study includes: mall and market, railway station, tourist attraction, public transportation, monument and memorial, bridge[56] and Bath Abbey[57].

To summarise, this comparative study investigated the following tactile landmark representation techniques: (1) manipulating the signal rhythms (Ternes & MacLean, 2008), and (2) increasing the number of actuators used to display information (Loomis & Lederman, 1986). We refer to the two techniques as the single-actuator and dual-actuator techniques respectively. We evaluated novel tactile representation techniques for the landmarks, both alone and in combination with the directional signals.

4.4.2 Basis for the study: underlying theories

MRT and Prenav model

For this particular experiment, we drew our expectation upon two underlying theories, MRT (Wickens, 1980; 1984; 1992; 2002) and Prenav, an integrated model of human navigation (Van Erp, 2007) (see Chapter 2 Section 2.4.1).

During the experiment, our participants would be asked to specify felt landmarks with and without the presence of direction signals. With direction signals (using a symbolic mapping technique), signals' meaning was believed to be recognised easily in a near-automatic manner (Klippel et al., 2005) whilst with landmark signals (using an abstract mapping approach), meaning was expected to be memorised during a considerable amount

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[56] The original list derived from interview sessions in Bath contains *river* which we considered not practical for tactile displays. We have replaced this landmark category with *bridge* which is an iconic non-continuous infrastructure situated just above the river in the real setting.

[57] The original list contain *religious place*. We simply replace this category with a unique religious landmark of the city, the Bath Abbey.

of training and later recalled (Garzonis et al., 2009). According to MRT, it assumes that the cognitive resource required for processing both the recognition of direction patterns and the recall of landmark signals would be the same. Although the MRT indicates the interference effect at the inter-sensory level, we predicted that interference would occur in our experiment because the two representation approaches demanded different levels of cognitive effort. This might result in a decrease in users' ability to recognise and recall signal meanings and associations.

Specifically, we assumed that the use of our tactile navigation display prototype follows the information processing loop of the Prenav model, which contains the circlet processes of sensation-perception-decision-action and back to sensation via the environment or the display (see Figure 2.5). In other words, our participants would sense an instance of spatial signals via the stimulated modality, the skin. Then, under the influence of cognitive resources such as memory and attention capacity, information would be further processed and interpreted into a percept. A percept may be stored in memory and may lead to a decision, e.g. to turn or which route to take, and eventually an action following such a decision. Then information from the environment or the system display will feed the next stimulus for the sensation process and so on.

A specification of Prenav is the existence of two shortcuts: the sensation->action and the perception->action shortcuts. The shortcuts bypass the cognitive ladder processing, i.e. perception->decision, hence, decreasing reaction time and mental effort. This phenomenon occurs when a sensation or a percept directly evokes an action that does not involve a conscious decision. Humans are able to react to stimuli quickly in this automatic manner because we possess innate reflexes and our sensory motor control for some tasks is well-trained (Van Erp, 2007). For example, if we have seen the visual representation of a green man at the pedestrian light, we cross the road; if a driver sees a red traffic light, they decelerate. It is the result of highly-trained skilled behavior of automated if-then rules. According to Prenav, the display that enables the two shortcuts is considered intuitive.

We expected that with the given training duration in the experiment, the presentation of directions would enable the shortcuts while the presentation of landmarks would require the full processing loop because it required the users to memorise signals' meaning association.

Dual Coding theory

The Dual Coding theory emphasises the powerful mnemonic effects of *visual* and *verbal* imageries on memory and learning (Paivio, 1986). The theory postulates that the human cognition consists of two subsystems, one processing pictorial and the other dealing with linguistic information. Whilst the two subsystems can be activated independently, the interrelations between the two systems allow simultaneous process, i.e. dual coding of information (Dual Code™, 2011).

To accommodate effective signal training sessions, we followed the Dual Coding theory by providing a set of images and a label for each vibration stimulus.

NASA task load index (NASA TLX)

To measure users' workload (i.e. cognitive effort), we use a Task Load Index (TLX), a subjective workload assessment tool developed by the United States government's National Aeronautics and Space Administration (NASA) (see Hart & Staveland, 1988). NASA TLX provides an overall workload score based on average ratings of six subscales including Mental Demands, Physical Demands, Temporal Demands, Own Performance, Effort and Frustration.

Following the example of a modified TLX in Fairclough (1991), we modified the original TLX so that it was suitable for measuring workload aspects of a wearable device being used for navigation tasks (see Appendix 4).

4.4.3 Research questions

This lab-based comparative study of tactile representation techniques for landmarks on a waist-belt wearable device was aimed at addressing the following questions:

> *RQ4: How can we represent spatial information via the chosen device? Specifically, which representation technique should be used for landmarks?*

Additionally, we would like to investigate the maximum threshold of human cognitive capacity for spatial information. Namely, whether users were able to perceive both direction and landmark signals effectively; if so, how many patterns they were able to memorise and recall after a considerable training duration.

4.4.4 Method: equipment and participants

Equipment

The same equipment and setting as in Chapter 3 was used (see Chapter 3 Section 3.3.3 and Figure 4.1).

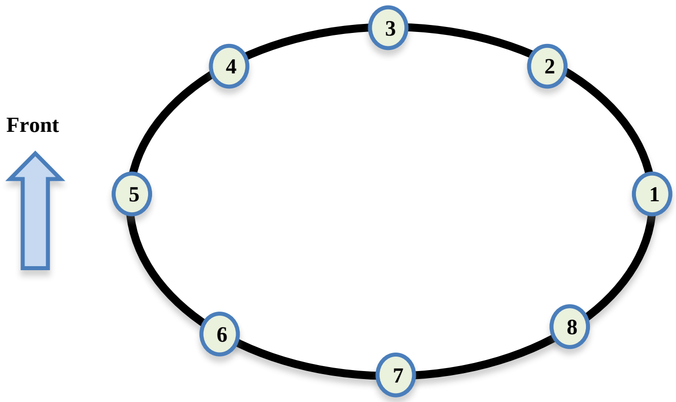

Figure 4.1 The Waist Belt Prototype (motor number 3 is the front centre actuator.)

Participants

There were 20 participants: 10 males and 10 females with an average age of 29 (SD=4.94, range 20-40 years). None of the participants reported irregularity with tactile perception around their waist at the time of the study. Participants' average waist size was 78 cm (SD=9.93, range 62-99 cm). We established from pre-test questionnaires that all participants understood the concept of "direction" and "landmark" and had no difficulties identifying them. Each of them received a five British pounds monetary incentive at the end of the experiment.

4.4.5 Tactile stimuli

The single-actuator technique for landmarks

For the single-actuator technique, we used *a set of 2-sec rhythmic stimuli* proposed by Ternes & McLean (2008). The rhythmic tactile stimuli set was designed by using *Eliminative heuristics and constraints*[58], a principled validation methodology based on

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[58] Eliminative heuristics and constraints (Ternes & MacLean, 2008):

E1: All notes have the same amplitude and frequency.
E2: A gap is required between successive notes.
E3: Overall duration is 2 seconds.
E4: Each base 500ms pattern should be repeated four times to create *rhythm*.
E5: The shortest note is 1/16 (31.25ms).
E6: There are five note lengths: whole (500ms), ½ (250ms), ¼ (125ms), ¾ (375ms), and 1/8 (62.5ms). Each includes 62.5ms off-time, except the 1/8 note that include 31.25ms off-time.

perceptual optimisation. Each stimulus in the set contains a number of pulses with varying duration of note lengths grouped together. There are five note lengths: whole (500ms), ½ (250ms), ¼ (125ms), ¾ (375ms), and 1/8 (62.5ms). Each includes 62.5ms off-time, except the 1/8 note that include 31.25ms off-time. Rhythm is then created as a repeated monotone pattern of variable-length notes, arranged relative to a beat (4/4) and played at a set tempo, manipulated by changing the length, number, or gaps between notes.

Positive selection heuristics[59], which are subjective rules that combine short and long notes (including gaps between them), allowed the generation of distinguishable tactile patterns. Figure 4.2 demonstrates the set of Ternes & MacLean's rhythmic tactile stimuli containing 21 signals. For example, a 2-second short stimulus contains a number of repetitions of ¼ notes (group 1 in Figure 4.2); a 2-second long stimulus contains repetitions of ¾ notes (group 2 in Figure 4.2); a 2-second mixed stimulus contains repetitions of ¼ and ½ or ¾ notes (group 3 in Figure 4.2).

Although signals have been systematically designed, tested and proved to be perceptible and distinguishable, Terne & MacLean's participants experienced vibrations through their hands and a stylus in the original studies. We were aware that different body locations have different sensitivity thresholds. In order to make sure that these stimuli were still distinguishable when displayed on the waist area, we ran a pilot session with four participants.

Results found that five out of 21 rhythms were clearly distinguishable (signals S1 to S5 in Figure 4.3). We further followed the positive selection heuristics by testing a combination of two of the five rhythms. As a result, signal S6 is a combination of S2 and S3; Signal S7 is a combination of S5 and S2. The final set of the most distinguishable rhythms is shown in Figure 4.3. Unlike the original illustration (Figure 4.2), each bar in our set represents a 1000ms stimulus, to be repeated two times as a 2 second stimulus. Each stimulus would be displayed on a single actuator.

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[59] Positive selection heuristics (Ternes & MacLean, 2008):

S1: Short notes – containing ¼ notes and gaps (group 1 in Figure 4.2)
S2: Long notes – containing ½, ¾, whole notes and gaps (group 2 in Figure 4.2)
S3: Mixed short and long notes – containing at least one ¼ note, other long notes and gaps (group 3 in Figure 4.2)
S4: Very-short replace short notes – replacing ¼ with 1/8 notes (group 4&5 in Figure 4.2)

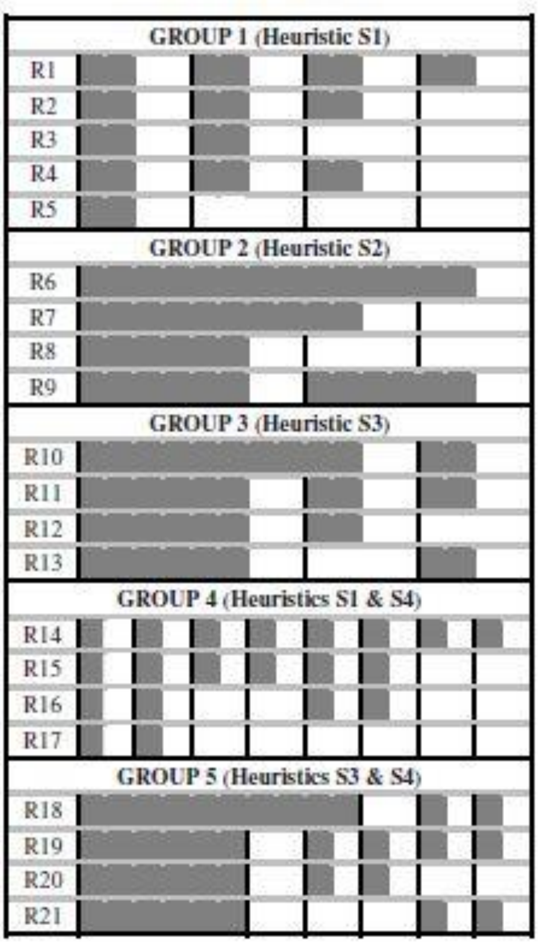

Figure 4.2 The rhythmic tactile stimuli set. Each row represents a 500ms bar, to be repeated 4 times as a 2-sec stimulus. Each note contains vibration on-(grey) and off-time (white) that separates it from the next. (Ternes & MacLean, 2008)

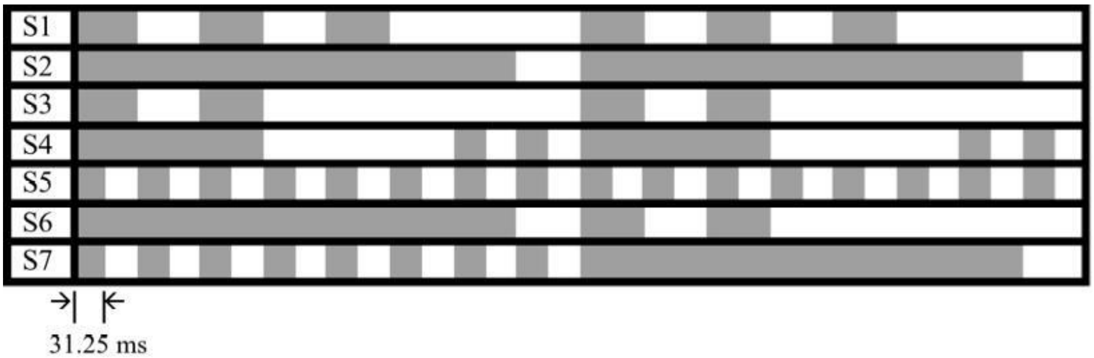

Figure 4.3 Single-actuator Landmark Signals. Each row represents a 1000ms bar, to be repeated 2 times as a 2-second stimulus. Each note contains vibration on- (grey) and off-time (white) that separates it from the next.

The dual-actuator technique for landmarks

In contrast to the single-actuator technique which used different vibration patterns to represent different landmarks, our dual-actuator technique used the same vibration pattern for all landmarks. The pattern used was the same as that for directional signals: a 1.2 second stimulus consisting of 12 repetitions of a 50-millisecond pulse and inter-pulse. The waist belt contains eight actuators; the different landmarks were represented by different combinations of actuators simultaneously providing the signal. Schiffman (1976) suggested that increasing the contact area of tactile stimuli would result in better perception and distinguishability among different types of information. Loomis & Lederman (1986) suggested that an effective approach to this would be to use multiple contact points; however, an optimum number was not suggested.

Our pre-pilot testing found several possible combinations to be indistinguishable from each other, e.g. six and seven adjacent actuators. Hence, we omitted these alternatives from further study. Then we ran a pilot study with four participants using the remaining combinations to find the optimum number of simultaneously activated actuators to represent our seven landmarks. During the pilot run, meaning association was not provided.

Pilot's tested alternatives included: (see Figure 4.1 for reference of actuator number)

(a) Pair of non-adjacent actuators, e.g. actuator pair 2-4

(b) Pair of adjacent actuators, e.g. actuator pair 2-3

(c) Three non-adjacent actuators, e.g. actuators 2-4-6

(d) Three adjacent actuators, e.g. actuators 1-2-3

(e) Four non-adjacent actuators, e.g. actuators 2-4-6-8

(f) Five adjacent actuators, e.g. actuators 1-2-3-4-5

Using NASA TLX, we measured mental demand, physical demand, temporal demand, effort and level of frustration. We also recorded localisation accuracy performance. Subjective distinguishability (both among the landmark signals themselves and from directional signals) and preference were gathered through questionnaires.

Overall results[60] from the pilot session suggested that the best arrangement was two non-adjacent actuators. This alternative received high scores on distinguishability and accuracy performance, and low scores on mental, physical and temporal demand and effort required. It should be noted here that for the waist belt device with eight actuators, the more actuators that were simultaneously activated, the more confused the participants were.

For ease of referring to the angles the belt is in the form of a circle; the final list of actuator pairs included: (see Figure 4.1 for referents of actuator numbers)

- 180º actuator pairs (3-7, 2-6, 1-5 and 4-8);
- 90º actuator pairs (1-3, 2-4, 3-5, 4-6, 5-7, 6-8, 7-1 and 8-2);
- 135º actuator pairs (1-4, 2-5, 3-6, 4-7, 5-8, 6-1, 7-2 and 8-3).

Directional stimuli

Figure 4.4 Direction Signals. A row represents a 1200ms bar, 12 repetitions of signals at 50- millisecond pulse (vibration on-grey) and inter-pulse (vibration off- white) duration, producing a 1.2-second stimulus.

Each directional tactile stimulus involved the actuation of one motor and consisted of 12 repetitions of signals at 50-millisecond pulse and inter-pulse duration, giving a 1.2 second stimulus (see Figure 4.4). The eight egocentric directions represented are: right, half right, straight, half left, left, sharp left, back and sharp right. Each actuator represented a direction based on its location around the participant's waist, with *straight* represented by

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[60] Descriptive statistics revealed the following:

Accuracy: The actuator pairs, both adjacent and distant ones, afforded high localisation performance in conditions both with and without the presence of directional signals.

NASA TLX revealed the following:

Mental, physical, temporal demand: All alternatives received nearly equal scores.
Effort: Participants indicated the more number of actuators, the higher the level of effort required.
Frustration: The more number of actuators, the higher the level of frustration.

Subjective ratings revealed the following:

Distinguishability: The pair of non-adjacent actuators received the highest subjective rating.
Preference: Participants preferred the pair of non-adjacent actuators.

the front centre actuator (see Table 4.3). For details on the design, generation and use of the directional signals see Chapter 3.

Table 4.3 Directional Stimuli

Stimuli code	**Vibrated Actuator Number (see Figure 4.1 for number reference)**	**Direction**
B1	1	Right
B2	2	Half right
B3	3	Straight
B4	4	Half left
B5	5	Left
B6	6	Sharp left
B7	7	Back
B8	8	Sharp right

4.4.6 Procedures

Experimental conditions

The experiment had two independent variables: (1) representation technique (the single- or dual-actuator techniques) and (2) the presence or absence of directional signals. The dependent variables were response time (in ms) and accuracy performance. Response time refers to the onset of the stimulus to the onset of the response, including the movement time. The experiments were divided into two stages with five conditions (see Table 4.4), two of the stage-1 conditions being repeated in stage 2. Each participant ran all conditions. In the first stage, we measured distinguishability, learnability and users' preferences. The first condition was a control condition in which only directional signals were presented. In conditions 2 and 4, only landmark signals were presented. In conditions 3 and 5, we presented directional signals together with landmark signals.

In stage 2, we measured the short term memorability of each type of signal. Approximately 30 minutes after participants finished conditions 2 and 4, we interviewed them and asked them to complete a set of questionnaires. They then repeated conditions 2 and 4. Both response time and accuracy performance were measured and compared with previous results in the first stage. Since our focus for the study was on landmark representation rather than directional representation, we did not repeat C3 and C5 during stage 2.

Table 4.4 Experimental Conditions

Condition	Stage	Direction	Landmark Single-actuator	Landmark Dual-actuator	Description
C1	1	✓			Direction only
C2	1		✓		Landmark (single-actuator)
C3	1	✓	✓		Direction + Landmark (single-actuator)
C4	1			✓	Landmark (dual-actuator)
C5	1	✓		✓	Direction + Landmark (dual-actuator)
C2r	2		✓		Landmark (single-actuator)
C4r	2			✓	Landmark (dual-actuator)

Hypotheses

For this lab-based comparative study of tactile representation techniques for landmarks on a wearable device, there were five hypotheses.

The vibration signals for directions are symbolically straightforward. They involve symbolic mapping of a limited set of directions to their respective vibration signals on corresponding parts of the body. In this and other research (e.g. Van Erp et al., 2005), there was an absolute point vibration for each designated direction on a distributed placement of actuators around the waist. On the contrary, the representation of landmarks used the abstract approach which required users to memorise signal patterns and their meaning associations in an effectively arbitrary manner. Hence, it was hypothesised that learning time required for landmark representations would be significantly longer than those for directions (*H1*) as participants have to learn the association between the signal and what it represents.

Previous research (e.g. MacLean, 2008; Tan et al., 2003) has suggested that humans can recognise 4-7 abstract tactile patterns and associate them with predefined meanings. We hypothesised that participants will be able to recognise landmarks with at least 80% accuracy in at least one non-control condition, either in condition 2 or 4 (*H2*). Based on the same previous research, we predicted that participants will be able to distinguish landmark from directional signals in conditions 3 and 5 (*H3*).

However, in conditions 3 and 5 where we present directional signals together with landmark signals, we hypothesised that the presence of direction signals will reduce participants' performance in recognizing landmark patterns (*H4*). This is due to the constraints on human memory and attention capacity (Schiffman, 1976). In both conditions, participants had to attend to directional signals then to landmarks and then provide responses.

While many researchers (e.g. Tan et al., 2003; Ternes & MacLean, 2008) have concluded that using different signal rhythms will effectively make stimuli distinguishable, the combination of two simultaneous actuator vibrations may make the iconic stimuli for landmarks unique (Loomis & Lederman, 1986; Schiffman, 1976) and clearly distinguishable from directional stimuli. With the single-actuator technique, signal patterns could be generated on an actuator that has just generated a direction signal, so participants might suffer from tactile adaptation, i.e. continued pressure stimulation that may result in a decrease of sensory experience (Schiffman, 1976). As a result, they might fail to distinguish between different signal types. Using two actuators to represent landmarks introduces discontinuity (Schiffman, 1976) that could help to make landmark signals perceptibly different from direction signals. Hence, we predicted that the dual-actuator technique would afford better performance than the single-actuator technique when representing landmarks on a waist-belt tactile display that provides both directional and landmark information (*H5*).

Experimental Procedures

Training – Measuring learnability

Participants were given a 4-phase training exercise to learn the signal patterns and their associations (assigned, counterbalanced across participants, by the experimenter). According to Sanderson et al. (2006), training with mnemonics[61] lowers the range of confusion and enhances training effectiveness. In a related study (Edworthy & Hards, 1999), researchers reported that verbal labels worked better than graphic images. We decided to provide both labels and images in order to magnify the mnemonic effect (Paivio, 1986). To summarise, during training, each vibration stimulus was given with the

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[61] Mnemonics refer to the ability to see visual description corresponding to the stimulus (Sanderson et al., 2006) according to the prediction of the dual-coding principle (Paivio, 1986; Sadoki & Paivio, 2004).

visual display of a label as well as a set of images. Images and labels used during the training are illustrated in Figures 4.5 to 4.11 for seven landmarks; and in Figure 4.12 for eight directions.

Figure 4.5 Landmark mnemonic for an iconic religious place in Bath, the Bath Abbey

Figure 4.6 Landmark mnemonic for mall and market

Figure 4.7 Landmark mnemonic for tourist attractions

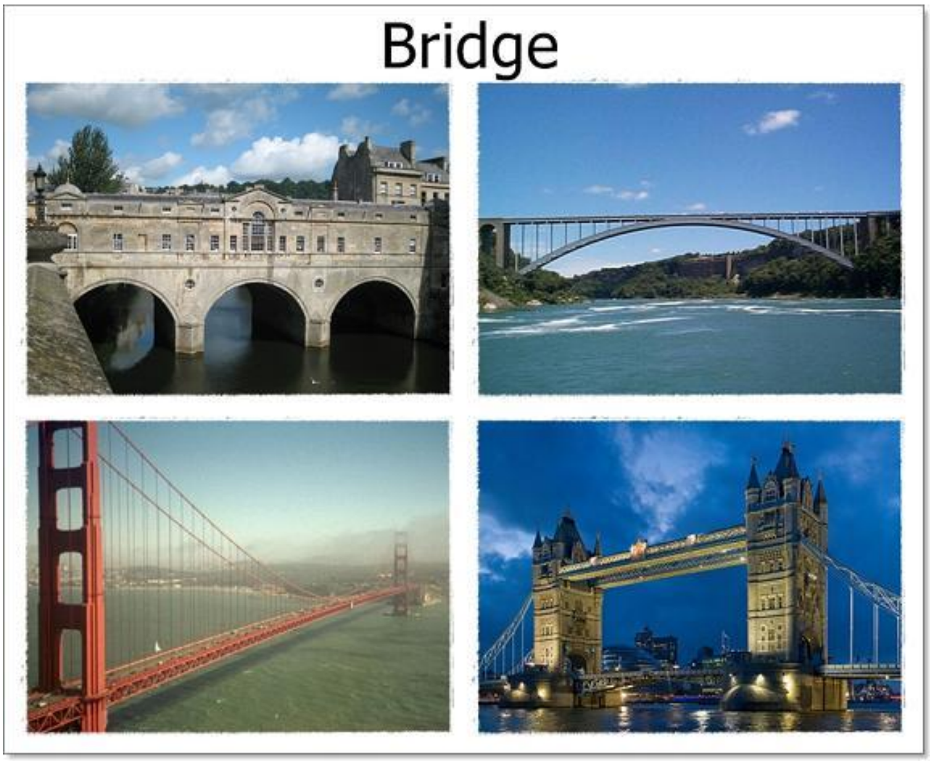

Figure 4.8 Landmark mnemonic for bridge

Figure 4.9 Landmark mnemonic for monument and memorial

Figure 4.10 Landmark mnemonic for public transportation

Figure 4.11 Landmark mnemonic for railway station

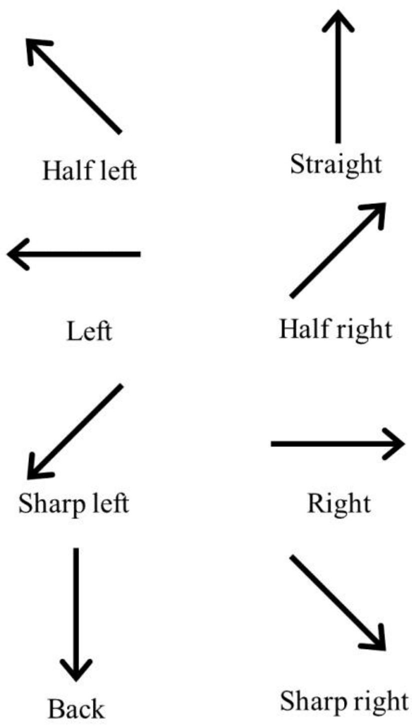

Figure 4.12 Direction mnemonics for eight egocentric directions

The 4-phase training consisted of display-memorise-trial-test phases.

In *phase 1 – display*, each vibration stimulus was generated twice along with its associated spatial mnemonic, i.e. a label and images of a landmark category. Phase 1 ended once all stimuli in the set had been presented. In *phase 2 – memorise*, participants were allowed to memorise the signals for four minutes. Participants were presented with images of directions or landmarks on a tablet PC screen. By clicking with a stylus on direction and landmark mnemonics on the screen, the system generated associated vibration signals. In *phase 3 - trial*, vibration signals were generated in a random order. For each generated signal, participants had to select the associated direction or landmark image according to what they had learned in phase 2. They received feedback whether it was correct for every selection that they made. Signals were repeated until the correct selection was made. Finally, in *phase 4 – test*, participants were presented with vibration signals and again they selected the associated direction or landmark. Phase 4 was similar to phase 3 but participants were given a performance score only at the end of the trial of either all eight direction or all seven landmarks. Feedback was in a form of percentage score of correct answers. Training stopped when participants scored over 71% or had been through 4 repetitions of the entire 4-stage process, whichever came first.

(Each participant then completed all five conditions in stage 1 and repeated conditions 2 and 4 in stage 2.)

Stage 1 – Measuring performance and distinguishability

In stage 1, we investigated whether performance with the two tactile representation techniques for landmarks differed in terms of learnability and distinguishability. The system generated tactile stimuli and participants identified perceived directions or landmarks by selecting corresponding mnemonic icons on a touch screen tablet PC. We measured: perceived directions, perceived landmarks and response time.

All participants started with C1. The order of experimental conditions C2-C5 was counterbalanced. Vibration signals in all conditions were generated in a pseudo-random order. In addition, landmark associations with vibration signals were systematically shuffled. Vibration signals and meaning associations were counterbalanced amongst participants.

In the control condition C1 (direction only), participants experienced 3 repetitions of 8 directions. In C2, C3, C4, and C5, participants experienced 21 signals (i.e. 7 landmarks x 3 repetitions) for each condition. Repetitions were introduced to mitigate the possibility that participants might make correct responses by chance.

In C2 and C3, the tactile single-actuator technique was used to generate landmark signals. In C2, only landmark stimuli were generated. In C3, the system generated a random directional signal, paused for 2 seconds, and then generated a landmark signal on the same actuator.

In conditions C4 and C5, the dual-actuator technique was used to generate landmark signals. In C4, landmark stimuli were generated on pairs of actuators. Of the seven landmark signals, four were generated using the 180º distance pairs. The other three pairs were a mix of pseudo-random 90º, and 135º pairs, counterbalanced on the left and the right sides and front and back of the body. We randomised the non-adjacent pairs and sought the optimum distance that provided the best performance. In C5, the system generated a random directional signal, paused for 2 seconds, and then generated a landmark signal on a pair of actuators.

Each stimulus was presented only once. When each tactile stimulus had been generated, participants were required to indicate (as "quickly and accurately" as they could) to which direction or landmark they thought it corresponded, by selecting one of the associated mnemonic icons on the tablet PC. The computer logged response time. Each session was followed by a short questionnaire capturing subjective data on distinguishability and learnability. When participants had finished all five conditions, they were asked to answer questions comparing the single- and dual-actuator techniques. They were also asked to reflect on their experiences with tactile communication. The final questionnaire took approximately 5-10 minutes to complete.

Stage 2 – Measuring memorability

In stage 2, we aimed to compare the two tactile representation techniques for their short term memorability. Stage 2 took place after participants completed distraction tasks, i.e. answering a questionnaire and discussing their experience of the experiment, approximately 30 minutes after they had been exposed to each type of landmark vibration stimuli.

Participants were asked to repeat conditions 2 and 4 in the same order that they had carried them out in stage 1. In each condition, each stimulus was presented only once. When each tactile stimulus had been generated, participants were required to indicate (1) the associated landmark by selecting an icon on the tablet PC and (2) their level of confidence in their answer on a 1 to 5 likert scale (1 being very unconfident and 5 being very confident). The computer also logged response time.

4.4.7 Results

Learnability

Information gathered during the 4-phase training session was used to analyse signals' learnability. Figure 4.13 demonstrates learnability effort required by three different representation techniques. At a glance, the charts show that participants spent significantly more effort to learn landmarks than to learn directions. They spent significantly higher average number of rounds, longer average time and higher number of training signals.

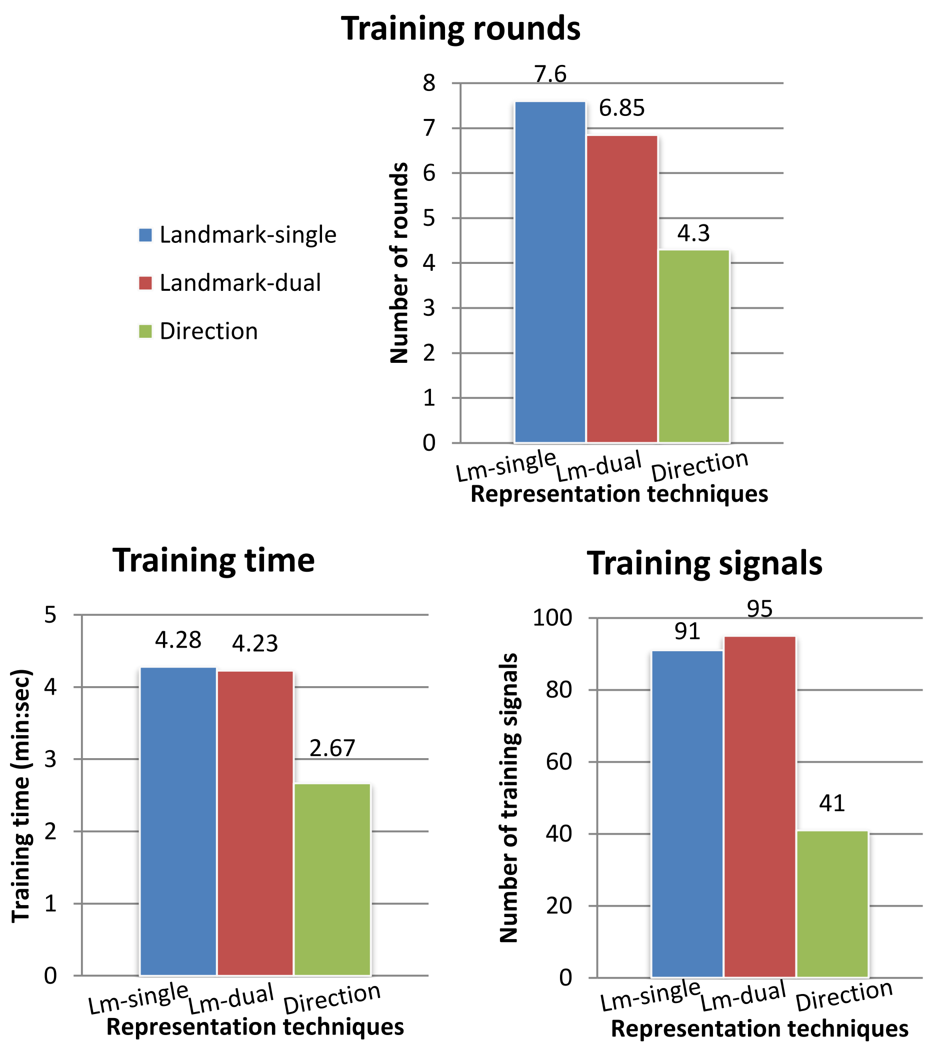

Figure 4.13 Training effort requirements of the three representation techniques

Tables 4.5, 4.6 and 4.7 present quantitative results on learnability in each phase in terms of average number of rounds, average number of signal trials, and average training duration.

Table 4.5 Training requirements: average number of rounds

Training phase	Direction	Single-actuator	Dual-actuator
Phase 1	1.20	1.65	1.65
Phase 2	1.05	2.40	2.05
Phase 3	1.00	1.00	1.00
Phase 4	1.05	2.55	2.15
Total	**4.30**	**7.60**	**6.85**

Table 4.6 Training requirements: average number of signals

Training phase	Direction	Single-actuator	Dual-actuator
Phase 1	10	12	12
Phase 2	15	54	61
Phase 3	8	7	7
Phase 4	8	18	15
Total	**41**	**91**	**95**

Table 4.7 Training Requirements: Average Duration (min:sec)

Training phase	Direction	Single-actuator	Dual-actuator
Phase 1	00:45	00:56	01:01
Phase 2	00:36	01:26	01:38
Phase 3	00:39	01:09	00:55
Phase 4	00:39	00:45	00:39
Total	**02:40**	**04:17**	**04:14**

A repeated-measures ANOVA (sphericity assumed) indicated that overall training requirements for all representation techniques were significantly different: number of training rounds, $F(2, 38) = 16.93$, $p < 0.01$, training duration, $F(2, 38) = 26.07$, $p < 0.01$, and number of signal trials, $F(2, 38) = 20.91$, $p < 0.01$.

The repeated-measures ANOVA results indicated that the amount of training requirements was significantly affected by different representation techniques, in each case, $F(2, 38)$, $p < 0.01$. Statistical data for each training phase is demonstrated in Table 4.8.

Table 4.8 Repeated-measures ANOVA results for training requirements: * indicates that the result is significantly affected by representation techniques (f2, 38, $p < 0.01$).

Training phase	Duration	No of Rounds	No of Signals
Phase 1	7.03*	7.03*	2.47
Phase 2	26.49*	11.07*	19.91*
Phase 3	6.11*	n/a	n/a
Phase 4	11.89*	12.78*	10.06*

Post-hoc pairwise comparisons (Bonferroni adjustment) indicated that training requirements for both landmark representation techniques were significantly greater than those for the directional technique in number of training rounds (both $p < 0.01$), training duration (both $p < 0.01$), and number of training signals (both $p < 0.01$). In other words, learning to associate landmark signals with their meanings required more effort than learning directions. These results were congruent with our expectation, hence, we accepted *H1*.

Prior to the study, we predicted that participants would spend more time and effort in learning landmarks with the single- than with the dual-actuator techniques (according to *H5*). No significant difference was found in training duration, rounds and number of signal trials between the landmark's single- and dual-actuator techniques (all three $p > 0.05$). In other words, participants spent as much time and effort on either technique.

In addition to the above analysis on learnability, we took an opportunity to analyse accuracy performance percentages from phase 4 of the training sessions. Participants passed phase 4 with mean scores of: direction 92.86% (SD=7.59), landmark single-actuator 83.57% (SD=19.81), landmark dual-actuator 84.28% (SD=15.99). Performance scores for all techniques showed no significant difference, $F(2, 38) = 2.82$, $p > 0.05$). Please note that this information was not included as our performance measurement (which will be reported in the next section).

Performance

Table 4.9 shows the means of accuracy and time performance results of different representation techniques from all experimental conditions in both stage 1 and stage 2.

We statistically analysed data from C1, C2 and C4 (see Table 4.9, 1st and 4th rows for mean accuracy and time respectively) using the repeated-measures ANOVA technique (sphericity assumed).

Results showed that the time to complete each condition (Table 4.9, 4th row) was not significantly affected by the type of representation technique, $F(2, 38) = 1.60$, $p > 0.05$).

Table 4.9 Mean performance: accuracy in %, time in mm:ss

Stage	Description	Direction	Single-actuator	Dual-actuator
1	Accuracy (C1, C2 and C4)	93.75	80.00	82.14
1	Accuracy after adding direction (n/a, C3 and C5)	n/a	68.1	81.43
2	Accuracy after distraction (n/a, repeating C2 and C4)	n/a	77.14	83.57
1	Average completion time (C1, C2 and C4)	01:22	01:40	01:37
1	Average completion time (n/a, C3 and C5)	n/a	03:08	02:33
2	Average completion time (n/a, repeating C2 and C4)	n/a	00:55	01:00

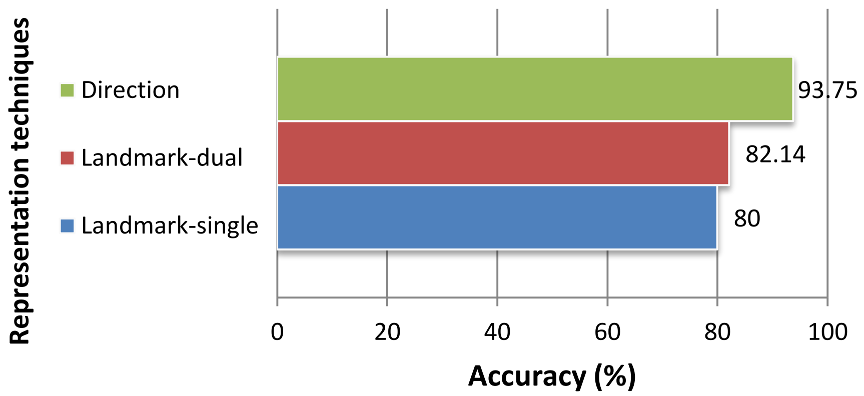

Figure 4.14 Accuracy performance (%) of the three representation techniques (means of C1, C2 and C4)

However, different techniques significantly affected accuracy performance, $F(2, 38) = 3.82$, $p < 0.05$ (Table 4.9, 1st row). Figure 4.14 illustrates accuracy performance (%) of the three representation techniques. Post-hoc pairwise comparison (Bonferroni adjustment) revealed that participants performed significantly better with directional identification than with both landmark techniques, (both $p < 0.05$). There was no difference in accuracy performance between the landmark single- and dual-actuator techniques ($p > 0.05$).

We predicted that participants would exceed 70% accuracy performance with either landmark technique. Results, in Table 4.9, 1st row, show that participants were able to recognise landmark signals with over 80% accuracy rate for both landmark techniques. Therefore, *H2* is accepted.

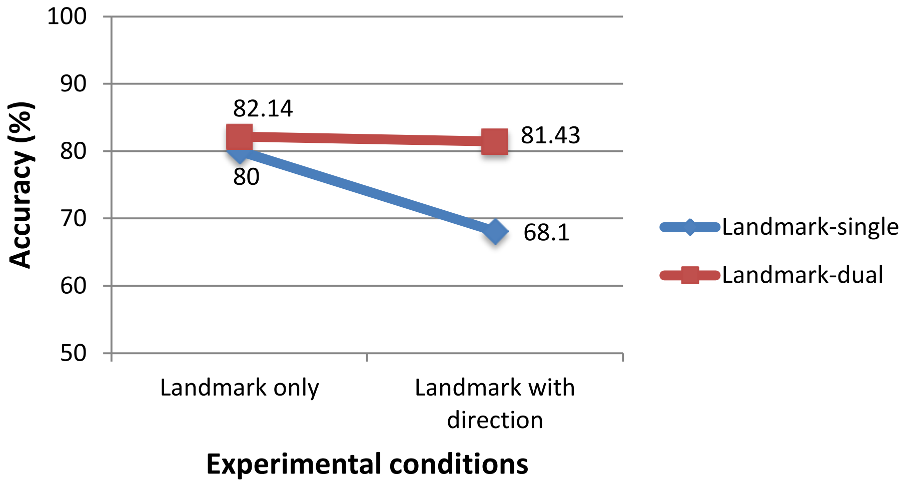

Figure 4.15 Landmarks' accuracy performance (%) with and without the presence of direction signals (mean values of C2 vs C3 and C4 vs C5)

We predicted that the performance of landmark signal perception would be affected by the presence of directional signals. For this particular case, means performance is shown in Table 4.9, 2nd row with Figure 4.15 illustrating a downward trend for the single-actuator and a stable performance for the dual-actuator technique. We ran a dependent t-test that compared accuracy performance of C2-C3 (single-actuator with/without direction) with C4-C5 (dual-actuator with/without direction). With the single-actuator technique, landmark identification performance was significantly lower when directional information was present than when it was absent, $t(19) = 2.65$, $p < 0.05$. In contrast, with the dual-actuator technique participants were able to identify landmarks equally well whether or not directional signals were presented, $t(19) = 0.32$, $p > 0.05$. Therefore, we reject *H4* since the presence of directional signals affected only the landmark single-actuator but not the landmark dual-actuator technique.

Memorability

In order to measure the landmark signals' memorability, we distracted participants with interviews and questionnaire sessions before asking them to repeat conditions 2 and 4. Results are presented in Table 4.9, 3rd and 6th row for accuracy and time performance respectively. Figure 4.16 demonstrates slight changes in means of accuracy performance after distraction.

Paired-samples t-tests showed no significant difference in forgetting rates between the two landmark representation techniques. There was no significant difference in accuracy performance between repeated C2 and repeated C4, $t(19) = -0.95$, $p > 0.05$; no significant difference in performance between C2 and repeated C2, $t(19) = 0.64$, $p > 0.05$, and no significant difference between C4 and repeated C4, $t(19) = -0.51$, $p > 0.05$.

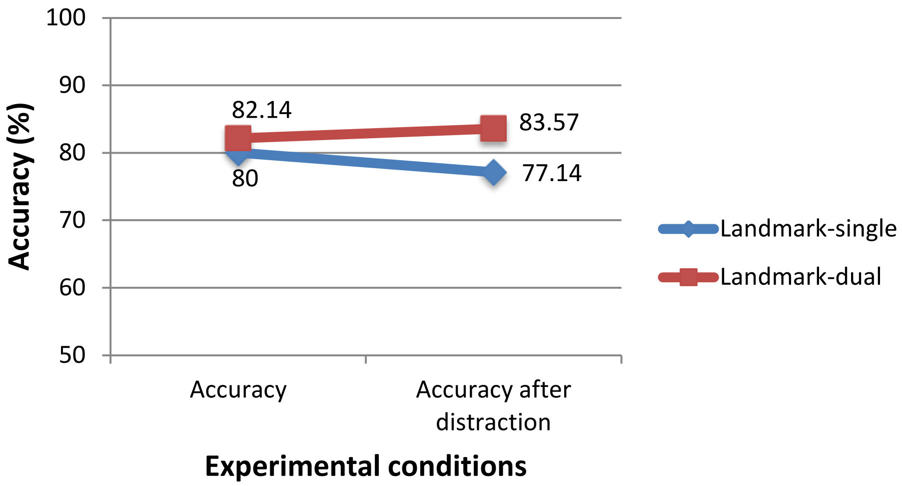

Figure 4.16 Landmarks' accuracy performance (%) before and after distraction (mean values of C2 vs C2r and C4 vs C4r)

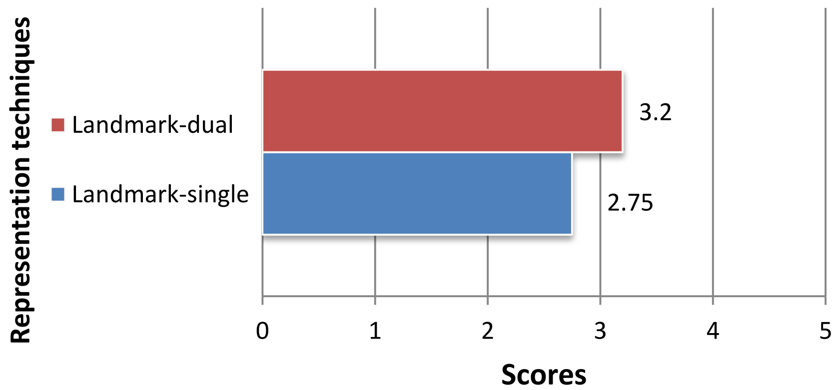

Figure 4.17 Landmarks' subjective memorability (n of 5)

Subjective memorability rating (means illustrated in Figure 4.17 and Table 4.10, 2nd row) also showed no significant difference between the two landmark techniques, $t(19) = -1.76$, $p > 0.05$. Hence, we concluded that both landmark representation techniques were equivalent in terms of short-term memorability.

Distinguishability and other subjective data

Post-questionnaires were used at the end of each experimental condition. We gathered user's subjective data on the two landmark representation techniques on several measures. They included: distinguishability from direction signals, distinguishability amongst landmarks themselves, memorability, ease of meaning association, and the level of directional signals' interference. Participants gave ratings on a 1-5 likert scale, 1 being low and 5 being high.

The single-actuator representation technique scored lower than the dual-actuator technique in all subjective measures except for distinguishability amongst landmark signals, in which it scored equal with the dual-actuator technique (see Table 4.10).

Paired-samples t-tests showed no significant difference in all subjective measures. Specifically, there were no significant differences between the two landmark representation techniques in: distinguishability amongst landmark signals, $t(19) = 0.00$, $p > 0.05$; memorability, $t(19) = -1.76$, $p > 0.05$; association with landmarks, $t(19) = -0.15$, $p > 0.05$; distinguishability from direction signals, $t(19) = -1.10$, $p > 0.05$; and level of interference with direction signals, $t(19) = 0.84$, $p > 0.05$.

Table 4.10 Average scores of subjective measures: n of 5 on a 1-5 likert scale, 1 being low and 5 being high.

Subjective Measurements	Single-actuator	Dual-actuator
Distinguishable among themselves	3.55	3.55
Memorable	2.75	3.20
Associable with landmarks	2.60	2.65
Distinguishable from directions	4.25	4.50
Interference with directions	2.55	2.30

Based on landmark accuracy performance and the subjective measurement scores on distinguishability (demonstrated in Figure 4.18), we conclude that all participants were able to distinguish landmarks from directional signals in both conditions 3 and 5. Therefore, we accept *H3*.

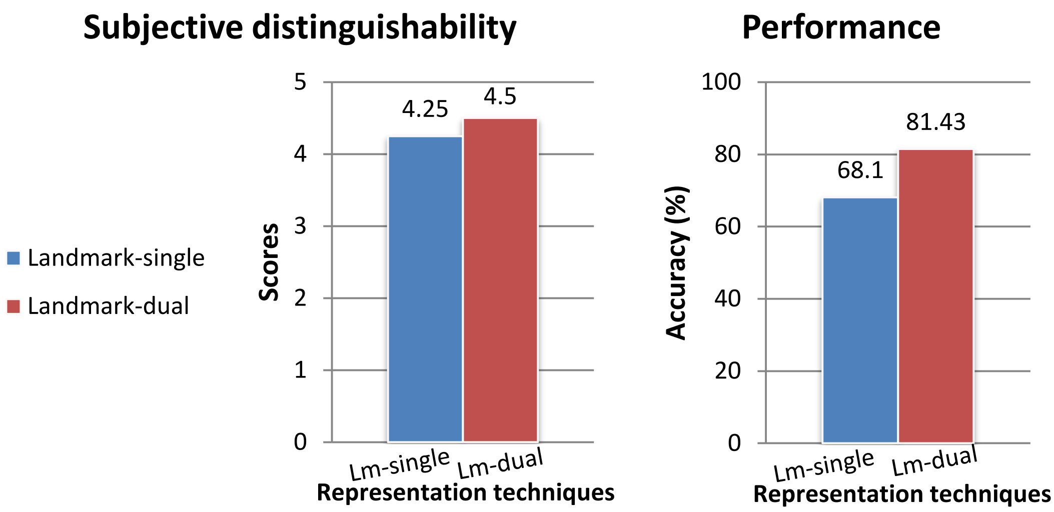

Figure 4.18 Left - Landmarks' subjective distinguishability (n of 5); Right – Mean accuracy performance of C3 and C5)

As for subjective preference between the two landmark representation techniques, while 12 participants (60%) preferred the dual-actuator to the single-actuator technique, paired-samples t-tests showed no significant difference in preference, $t(19) = -0.89$, $p > 0.05$. Whichever technique a participant preferred, their comments and reasons were very similar and included "easy to remember and interpret", "more natural", and "easy to associate with landmarks".

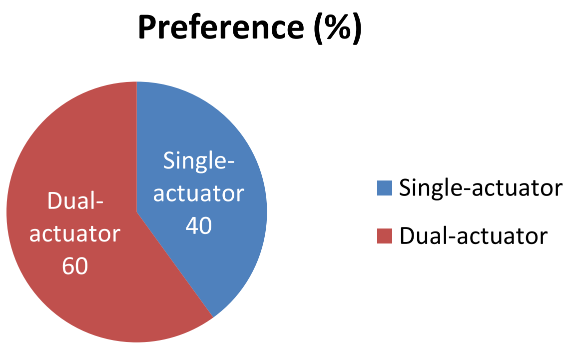

Figure 4.19 User's preference

If we look carefully at accuracy performance, each participant performed better with his or her preferred technique in C2 and C4. However, in C3 and C5 (when directional information was presented), performance of participants who preferred the dual-actuator technique dropped drastically when they carried out the single-actuator condition, while that of participants who favoured the single-actuator technique remained similar in both conditions. As a result, we found a significantly low overall accuracy performance score in condition 3.

Overall

Results showed that the single- and dual-actuator techniques offered almost equal support for landmark representation. To be precise, they required equal amounts of training (approximately four minutes) and users performed equally well (~80% accuracy) in experimental conditions in which only landmark signals were presented.

However, both direction and landmark information is crucial for navigation completion and should be provided in an operational tactile pedestrian navigation system. According to the accuracy performance results of C3 and C5 (Table 4.9, 2nd row), participants were able to perform significantly better with the dual-actuator technique than with the single-actuator technique when landmark signals were presented together with directional signals $t(19) = -2.63$, $p < 0.05$. In addition, the performance of the dual-actuator technique remained consistent after a 30-minute distraction task whilst that of the single-actuator technique decreased. Therefore, *H5* is accepted that the dual-actuator affords better performance than the single-actuator technique.

Detailed results

The single-actuator technique

For the single-actuator technique, detailed results on the accuracy of each pattern are presented in Table 4.11.

Table 4.11 The single-actuator's accuracy performance (%) by signals (see reference in Figure 4.3)

Signals	C2 – landmark only	C3 – landmark + direction	Repeated C2
S1	68.33	63.33	70.00
S2	88.33	76.67	90.00
S3	78.33	73.33	75.00
S4	71.66	43.33	65.00
S5	93.33	83.33	90.00
S6	83.33	60.00	65.00
S7	81.66	75.00	85.00

Participants performed well with the patterns containing repetitions of only a very short note (i.e. a 1/8 note – 62.5ms including 31.25ms off-time) or a very long note (i.e. a whole note – 500ms including 62.5ms off-time. These patterns included the S5 (only 1/8 notes), S2 (only whole notes) and S7 (a mix of 1/8 and whole notes) in descending order by accuracy performance. Accuracy performance of the best (S5) and the worst (S4) patterns was significantly different ($p < 0.05$).

We did not have prior expectation on the effect of different patterns on accuracy performance. In the original study, researchers (Ternes & MacLean, 2008) maintained that rhythms would be easily distinguished primarily by note length and "evenness". Evenness is defined by a consistent repeating nature of notes and gaps in which each part of the rhythm feels the same as every other part, throughout the duration of the stimulus (Ternes & MacLean, 2008). Our results confirmed the original study's results provided that participants achieved high accuracy performance with signals that possess high level of evenness.

The dual-actuator technique

For the dual-actuator representation, we varied the pairs of actuators used. All the 180^o actuator pairs were used by all participants. Other pairs were distributed evenly across all participants. Detailed results of each actuator pair are presented in Table 4.12.

Table 4.12 The dual-actuator's accuracy performance (%) by actuator pairs (see number reference in Figure 4.20)

Actuator Pairs	C4 – landmark only	C5 – landmark + direction	Repeated C4
3-7	90.00	98.33	95.00
2-6	80.00	75.00	80.00
1-5	96.67	95.00	90.00
4-8	71.67	68.33	75.00
1-3	100.00	100.00	66.67
1-7	100.00	66.67	100.00
2-4	100.00	100.00	100.00
2-8	88.89	72.22	100.00
3-5	88.89	66.67	66.67
4-6	85.71	80.95	85.71
5-7	86.67	73.33	100.00
6-8	100.00	100.00	83.33
1-4	41.67	75.00	75.00
1-6	66.67	66.67	50.00
2-5	83.33	83.33	100.00
2-7	55.56	66.67	100.00
3-6	33.33	44.44	33.33
3-8	88.89	100.00	100.00
4-7	66.67	83.33	100.00
5-8	58.33	66.67	50.00

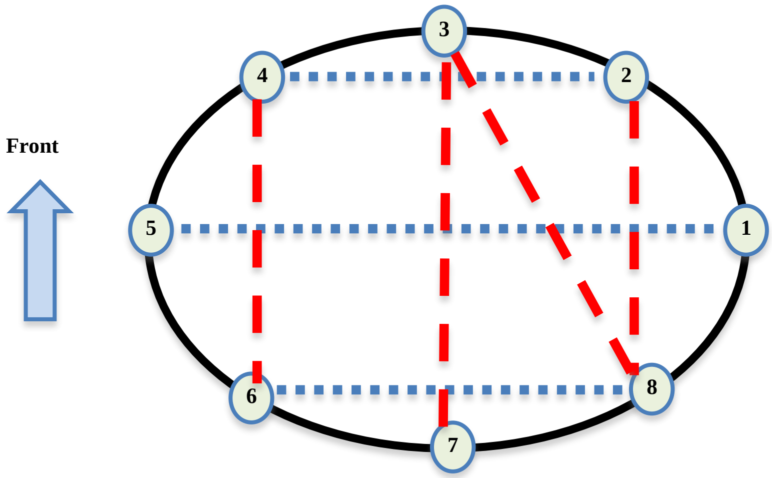

Figure 4.20 Best actuator pairs (motor number 3 is the front centre actuator). Horizontal lines show the three best pairs: 2-4, 1-5, 6-8; vertical lines demonstrate the next best three pairs: 2-8, 3-7, 4-6. The diagonal line shows the next best pair: 3-8.

Participants performed well with the actuator pairs that were horizontally or vertically aligned with their body. These pairs included the 2-4, 1-5, 6-8, 2-8, 3-7 and 4-6 pairs. The next best pair was the 3-8 pair. The actuator pairs which afforded the highest performance are demonstrated in Figure 4.20. We recommend choosing these seven pairs to represent our set of seven landmarks in a tactile navigation aid.

Prior to the study, we expected participants to have performed well with the two diagonal 180° actuator pairs (i.e. the pairs 4-8 and 2-6). However, results revealed that asymmetric or diagonal pairs did not support good performance.

4.4.8 Discussion

Learnability

Overall, the results supported the hypothesis *H1* on learnability that it was easier to learn direction than landmark. In fact, it was obvious that users did not ‘learn’ directions’ associations, but rather they used prior knowledge on egocentric directions to make connections with locations of vibrotactile stimuli around their waist. This has been demonstrated earlier in the experiments described in Chapter 3 that participants achieved a very high level of accuracy performance in direction identification even without being trained.

For the learning of landmarks, participants were required to establish an association between the signal and the landmark it represented. In the current study, the experimenter assigned the associations between signals and landmarks for each participant (but we counterbalanced the meaning associations across participants) because we would like to eliminate any learning effect or bias that may occur on each particular stimulus. We have not gathered much of an interesting insight as to which strategy participants used to learn both sets of landmark stimuli. Only one female participant described the detail of her memorisation techniques while others merely indicated that they tried to memorise the given associations without any underlying semantics.

The one participant specified that she used several techniques. For some patterns, she associated vibrations with the location of the landmark mnemonic on the screen. Sometimes, she made several connections for an association, e.g. first, linking vibration to a familiar natural sound then the sound with a specific (personal) meaning, and then the meaning with the landmark on the screen. Another interesting technique was when she made an association of her survey knowledge of the city of Bath with the stimulated location on her body. If the signal and the actual place happened to be in the same or similar direction, she felt that she could remember it better. However, for this particular participant, her performance with the single-actuator conditions was very low (lower than 30% accuracy) and with the dual-actuator conditions was moderately low (approximately 55-60%); response time was exceptionally slow across all conditions.

We can conclude that our participants used two strategies: 95% memorised associations and 5% sought related mental concepts to form associations. In a related study, though in an auditory design space, Bonebright & Nees (2007) have reported that when it came to memorising arbitrary associations, 30% of users tried memorizing, 35% tried to form a relationship, 27% tried to think of a story or images that formed associations, and 8% used the localised stimuli as cues. However, in Bonebright & Nees's (2007) study, the sound used was auditory icons[62] (Gaver, 1997) which were considered semi-arbitrary whilst the vibrations used in our study were completely arbitrary patterns. Hence, it was difficult for our participants to form relationships because there were no symbolic links available; the one participant who attempted to form semantic associations failed quite miserably.

[62] Auditory icons use metaphoric mapping to associate sound with information or events, e.g. the sound of shattering dishes represent the drop of a virtual object into the virtual recycle bin (Gaver, 1997).

Some participants mentioned that if obvious patterns (of the single-actuator signals) or symmetric motor pairs (of the dual-actuator signals) matched the most unique landmark in the mnemonic set, e.g. the Bath Abbey – the city's most unique landmark, it was very easy to recall. In this particular case, it seems that signals' salience relative to landmark uniqueness would lead to a better association. However, this assumption requires further investigation. Provided this limited knowledge, we have yet to determine, if any, a rationale that contributes to the ability to make associations, memorise and later recall landmarks in the tactile interaction domain.

There is very little research evidence which can be used to assist the decision on how to teach arbitrary association effectively (Edworthy & Hards, 1999). Nevertheless, it is suggested that learnability can be improved if participants develop their own semantics, i.e. participants themselves define associations between vibrotactile signals and landmarks (Cohen, 1993; Cohen, 1994a; Cohen, 1994b; Edworthy & Hards, 1999; Bonebright & Nees, 2007). This may be possible because a few of our participants suggested specific associations between signals and their meanings they preferred. Another suggestion is to improve the quality of imagery, i.e. word labels and pictures (Edworthy & Hards, 1999). We would take these recommendations into consideration for further training improvement.

Memorability

Our experimental study assessed learnability and short-term memorability and we have obtained some promising results. However, our results were based on a very short pause and a distraction task which lasted altogether approximately 30 minutes. It is not possible to determine the effects of longer term use. A longitudinal study is required to address such issues.

Performance

Our study was carried out under experimental conditions, which were likely to achieve different performances than in operational contexts (Sanders & McCormick, 1992). Experiments normally take place in a short time span and the experiment design usually aims to give participants high exposure to stimuli of interest, e.g. in our study, vibrotactile stimuli were provided as a series with very short intervals between them. On the contrary, in operational environments, landmark signals may be generated with a much longer lapse between them owing to different areas' morphology and locations of landmarks on routes. However, pedestrians will be able to look around and may perceive some environmental cues, which may help to identify landmarks, or even able to see the landmark itself to the extent that the vibrotactile cue becomes a redundant piece of information. Also it is possible that other noises in the environment may lower the vibration perception. Therefore, it is unclear whether the results from lab-based studies over- or underestimate the performance likely to be achieved in the operational setting (Edworthy & Hards, 1999).

Participants had an average response time of four seconds per signal across all conditions. This value is probably just about satisfactory for the intended use. Nevertheless, if these signals were to be used in outdoor urban environments, performance levels might drop since there are several other factors such as different levels of users' cognitive load and levels of noise. We anticipate that further training might help decrease response time in the lab setting, which might in turn reduce response time in applied environments. Further study is necessary to investigate whether extensive training or different training strategies (e.g. Edworthy & Hards, 1999) can better the performance and the extent to which external factors such as noise might affect the results and system robustness, especially in the field.

It is also worth noting that the tactile signal is brief and skin perception adapts through time so continued stimulation may lead to a decrease or even elimination of the sensory experience (Schiffman, 1976). This may cause some missed signals in use. One participant explicitly indicated that she experienced quick skin adaptation with the single-actuator conditions because landmark vibrations were sometimes generated on the same location as did directional signals. In real life, pedestrians are bound to split their attention between the system and the environment. Therefore, if the single-actuator technique is used and they miss the beginning of the pattern, it will be difficult to guess which one it was.

Distinguishability

We have compared two classes of tactile stimuli and the results indicated that the dual-actuator was more difficult to distinguish than the single-actuator patterns. However, if we look at individual signals, there were three specific patterns (signals S5, S2 and S7) that achieved very high levels of accuracy performance because of their "evenness" character. These three particular signals seem to be salient enough to be able to present other types of spatial information if necessary.

We speculate that this quality of "evenness" may help to improve the distinguishability rate of the single-actuator technique. For example, evenness can be achieved by adding more types of note length, e.g. a 1000ms or a 750ms, and having them repeated with gaps within the 2-min second stimulus. The idea is theoretically possible (Ternes & MacLean, 2008) but has yet to be investigated.

However, with the single-actuator technique, frustration was reported to occur when direction and landmark signals happened to be presented on the same actuator. In which case, participants reported that it felt like a continual buzz rather than two separated stimuli.

Based on subjective feedback, most participants found it easier to memorise the dual-actuator patterns because they felt the same regardless of stimulated locations. In other words, they found it easier to focus on locations than on patterns.

Limitations of the study

We were aware that vibrotactile signals produce acoustic output (Van Erp, 2002) which may have affected vibration perception. We have discussed the same issue earlier in Section 3.3.6 that our observation and analysis of the first two lab studies did not find any negative effect given that both vibration signals and acoustic output do not conflict with each other. Hence, in this study we did not have our participants wearing a noise cancellation device during the experiment. Same as in previous lab studies, none of our participants reported their focus of attention on sound localisation during the experimental session.

In our previous empirical studies (Chapter 3), we have reported that in some cases small body size had a negative effect on signal perception. In this study, we tried to recruit participants with a moderate waist size. However, two of our participants had rather a small waist (less than 70 cm). After checking detailed data of the two participants, they performed equally well as other larger participants.

4.4.9 Conclusion of the lab-based experiment

In this section, we reported an empirical study which compared two techniques to represent landmark information via the tactile channel in order to address RQ4.

> *RQ4: How can we represent spatial information via the chosen device? Specifically, which representation technique should be used for landmarks?*

As we hypothesised, participants took a significantly longer time to learn landmark signals and their associations compared with directional signals. With the presence of directional signals, performance of landmark identification significantly dropped for the single-actuator technique and remained the same with the dual-actuator technique. With training, participants were able to distinguish landmark signals from directional signals and recognised over 80% of learned landmarks. With respect to both techniques' forgetting rates, it appeared that they were equal. Should the navigation system display only landmark information, either technique is equally effective.

However, results from our study suggested that the dual-actuator technique was better than the single-actuator technique in various ways, especially as it afforded better performance when presented together with directional signals. This is crucial to the development of a tactile pedestrian navigation system that provides both directional and landmark information.

4.5 Summary

In this chapter, we have attempted to answer *RQ2(landmark usage)* and *RQ4 (landmark representation).* The next step was to refine the tactile navigation prototype for use in field trials.

Our results have shown that the dual-actuator approach achieved acceptable performance. Through a device capable of presenting the information with a number of actuators, users perceived the vibration signals quite well and they were able to recognise the signals' meanings as well as distinguish two types of spatial information.

Nevertheless, results presented here reported mainly on learnability and distinguishability performance of the two types of spatial information in a controlled environment. Whether they can be used together effectively in operational environments and help to improve navigation task's performance requires further investigation.

We would build on the insights from the lab-based work reported here and in the previous chapters to improve signals' learnability and investigate specific applications' utility and practicality in the field study. Through these investigations, we improved and evaluated the design and addressed user acceptability, and the performance-related benefits and challenges of a wearable tactile pedestrian navigation system. The field evaluation of a refined tactile navigation system is reported in the next chapter.

If you do not know where you come from, then you don't know where you are, and if you don't know where you are, then you don't know where you are going. And if you don't know where you're going, you are probably going wrong.

(Terry Pratchett, 2010)

Chapter 5 A Field Evaluation of a Tactile Display for Pedestrian Navigation

5.1 Introduction

The work described in this chapter is the third part in a series of empirical studies that aim to display landmarks together with direction signals through the touch sensory channel. The series has been divided into three steps: (1) an investigation of how landmarks are being used for different navigation purposes in urban canyons and the selection of appropriate landmarks – presented in Chapter 4, (2) a tactile representation technique for landmarks – also presented in Chapter 4, and (3) an evaluation of a tactile-based navigation system that provides various types of spatial information in an urban environment – presented in this chapter.

The focus of this chapter is on the design, development and evaluation of our tactile navigation prototype, built upon requirements developed throughout the thesis.

In this chapter, there are five subsections. In Section 5.2, we describe the motivation and research questions addressed by the studies. Next, in Section 5.3, we explain the basis of the study including underlying theories and relevant literature. Details of a field evaluation including methods, procedures, results and discussion are demonstrated in Section 5.4. Finally, Section 5.5 summarises the findings from our empirical field-based evaluations.

5.2 Motivation and objectives

This final part in the series of studies is the pinnacle of our research project. We aim to further research tactile pedestrian navigation beyond the current emphasis on directional cues by providing multiple types of spatial information necessary for navigation completion in real environments.

Although researchers suggested that, theoretically, the delivery of multiple spatial information types via the touch sense is possible and will be highly beneficial for navigation in both normal and extreme situations, Wickens, (1980); Van Erp et al., (2006) and Elliott et al., (2010), all reported that the empirical study of hybrid[63] systems that provide both direction and landmarks is rarely prevalent.

We have successfully tested the direction/landmark hybrid concept in a laboratory setting and reported satisfactory results in Chapter 4. As only a little research has addressed the practicality of such systems, in the next step we aimed to evaluate such a display in real contexts because mobility and involvement of real users in the changing environments can only be realised in the real-world (Ross & Blasch, 2002). We were aware that field-based evaluation has limitations in that there is limited control over the experiments and data collection is difficult (Kjeldskov & Graham, 2003). Nevertheless, it is a trade-off for increased realism that we would achieve through testing the system in the real-world.

The field-based evaluation manipulated the presence of signals for landmarks at specific points on routes. We also aimed to gather performance-related data regarding practical use of the tactile display in urban canyons. In addition to the report on design, usability and user experience issues, we hope to discuss navigation stages of tactile wayfinding in comparison with those in visual wayfinding.

5.2.1 Research questions

Throughout Chapters 3 - 4, we have demonstrated that the design of our prototype has achieved usability goals[64] in three lab settings and one field study. The next step is to incorporate the display of landmarks in the system and put it to test in real settings in order to understand the effect of represented tactile signals on users' cognition, judgment, association, navigation behavior and performance.

As a result, this study addresses *RQ4*

> *RQ4: How can we represent spatial information via the chosen device? Specifically,*
>
> > *RQ4.2 How do we represent a few types of spatial information?*

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[63] Throughout this chapter, the word *hybrid* refers to a system that provides more than one type of spatial tactile information.

[64] Usability goals include effectiveness, efficiency, safety, utility, learnability and memorability (Sharp et al., 2011).

And *RQ5*

RQ5: What is the tactile navigation system's performance?

RQ5.1 Does the system help with different tactile navigation purposes?

We have partially addressed *RQ5.1* in Chapter 3 by demonstrating that the tactile navigation system did help with quest. In this chapter, we aimed to find out whether it helps with exploratory navigation. Additionally, we address the following usability-related *RQs*.

RQ5.2 Can tactile landmark representation "increase/help" with performance/confidence as in visual pedestrian navigation systems?

RQ5.3 Is there a problem with the transfer of frames of reference with tactile navigation displays?

For the user experience aspects, the work in this chapter addresses the following RQ:

RQ5.4 What are user acceptance and perceived usefulness (practicality) of the tactile navigation system?

5.3 Basis for the study

This section describes underlying theories and concepts, summarises past findings, and discusses relevant literature.

5.3.1 Underlying theories and concepts for this study

For both studies presented in this chapter, we relied on the same underlying theories explained in Chapters 2 and 4 including MRT (Wickens, 1980), Prenav (Van Erp, 2007), Choremes (Klippel, 2003), and other guidelines for the design of tactile navigation systems (see Chapter 2 Section 2.4.1; Chapter 4 Section 4.4.2). We used the same training approach, following the Dual Coding theory (Paivio, 1986), as we did in Chapter 4. In this subsection, we briefly explain Technology Acceptance Model (TAM) that we used for the analysis regarding the system's practicality in actual situations and environments in which the system will ultimately be used.

Measuring user acceptance

Amongst a number of theoretical approaches to understanding the psychology of user acceptance (see a review in Dillon & Morris, 1996), we have chosen the Technology

Acceptance Model (TAM)[65] proposed by Davis (1989; 1993). TAM determines user acceptance by two factors: perceived usefulness and perceived ease of use. Perceived usefulness refers to the degree to which a user believes that using the system will enhance their performance. Perceived ease of use refers to the degree to which the user believes that using the system is effortless. The original TAM was modified (see Appendix 3) and used in our study to predict how pedestrians will likely receive the tactile navigation system.

5.3.2 Relevant literature and design challenges

As we have described in Chapter 2 (Section 2.4.2) the attempts to represent the second type of spatial information in tactile wearable displays focused on the addition of distance information (see Raisamo & Myllymaa, 2010; Pielot & Boll, 2010; Pielot et al., 2010c; Van Veen et al., 2004). Although most current assistive navigation technologies provide distance-based wayfinding instructions, displaying distance in pedestrian navigation systems is criticised to be an inappropriate choice because of the nature of pedestrians' slow moving speed (May et al., 2003), a human's poor judgment of distance (Ross et al., 2004), and the current setback of technology advances in measuring precise distance at ground level (RIN, 2011).

None of the reported research has attempted to represent landmarks despite suggestions from many studies (i.e. Vinson, 1999; Burnett et al., 2001; Baus et al., 2007) that pedestrian navigation systems could achieve better performance with the addition of landmarks.

As a result, we aimed to test our prototype to further research the domain of tactile pedestrian navigation. Outcomes from our and previous lab studies allowed us to predict that users would be able to use a hybrid tactile navigation system to aid their wayfinding effectively in the actual settings. Specifically, a field evaluation of the system would achieve an acceptable level of navigation performance.

Nevertheless, evaluating a system in the field may introduce numerous factors which might impede navigation performance using a tactile wearable system. For example,

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65 Since our thesis does not mainly focus on the technology acceptance issue, we opted for the original version of TAM to get preliminary insights into the acceptance of a unimodal tactile wearable device for navigation tasks. For a summary of TAM development, see Appendix 3.

participants' movement may decrease vibration detection (Karuei et al., 2011) and the visual workload and unexpected vibration may slow users down. Testing our improved system in the actual environment is mandatory; however, the system trials must be carefully designed and must take into account a human's limited cognitive capacity.

5.4 Field evaluation: A comparative study of tactile landmark presentation for pedestrian navigation

5.4.1 Overview

It is reported that in visual navigation, landmarks are always being used as confirmation cues to help increase navigation performance and confidence which in turn construct the navigator's survey knowledge (Pielot & Boll, 2010). We are interested in finding out whether landmarks hold the same value in tactile navigation as in visual navigation. On that account, our field evaluation saw the system trigger a set of landmark signals when a navigator was approaching a particular landmark category in one of the experimental conditions.

Notwithstanding a *straight* signal being used effectively as a confirmation cue (reported in Chapter 3), there is no other evidence on the effect of the *straight* signal. As a result, we are interested in finding out whether the *straight* signal, given at the exact same location where a navigator was approaching a particular landmark category, would yield the same effect to the landmark signals.

In addition to the main objective described above, we have two additional objectives: (1) improve landmark signals' learnability and (2) ensure landmark signals' memorability prior to the actual field comparative study. Hence, the experiment was divided into two stages: training and walking. In the training stage, we measured learnability and memorability. In the walking stage, we measured navigation performance, level of confidence, and system's perceived usefulness.

Training stage

To improve the learnability of landmark signals' association, we improved mnemonics' quality and provided a visual illustration of stimulated actuators and their associations to half of the participants. To ensure memorability, we made sure that each participant achieved 100% accuracy performance in the two training sessions (called T1 and T2, scheduled a few days apart) prior to the walking sessions (see Table 5.1).

Table 5.1 Training sessions

Session	Direction	Destination	Landmark
T1	✓	✓	✓
T2	✓	✓	✓

Walking stage

The field experiment examined the usage and the effectiveness of *straight* signals in comparison with *landmark* signals. The two experimental conditions would be referred to as conditions SS and LM for *straight* and *landmark* signals respectively (see Table 5.2).

Table 5.2 Experimental conditions – walking sessions

Signal type / Condition	Direction	Destination landmark	Straight signal	Landmark
SS	✓	✓	✓	
LM	✓	✓		✓

5.4.2 Method: participants, equipment and tactile stimuli

Equipment

We have modified our original[66] TactNav system so that it provides three types of spatial information, namely, directions, landmarks and destination cues. The power system has been changed from one 6v Yuasa battery to eight 1.2v-AA Uniross batteries for flexibility; a NASA marine compass sensor has been added. Figure 5.1 demonstrates the new system architecture.

[66] The original TactNav provided two types of output: egocentric directions and confirmation cues. Positioning functionality was facilitated by a GPS technology (see Chapter 3 Section 3.4.3 Figure 3.22 for the original design).

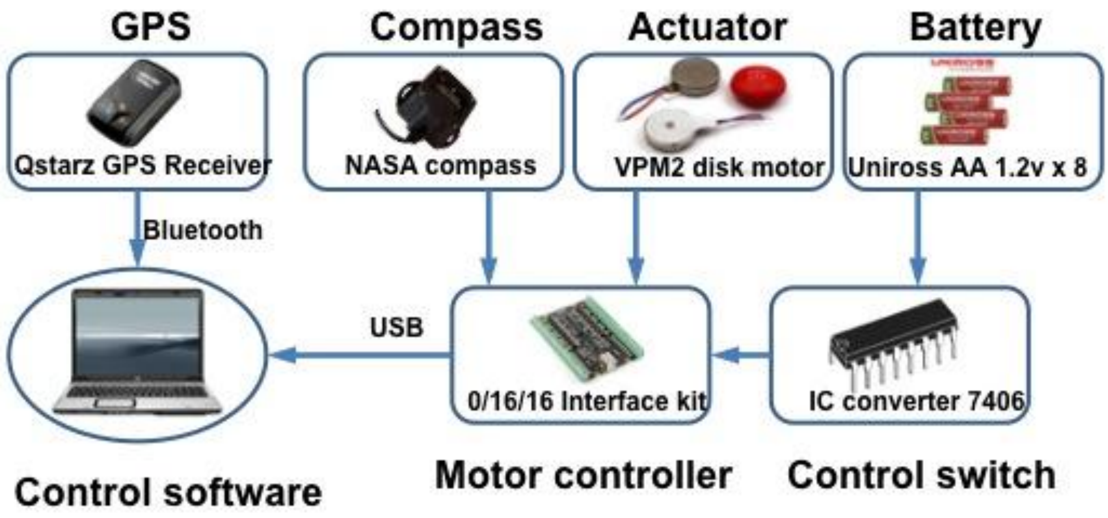

Figure 5.1 The new TactNav system architecture. A NASA marine compass sensor is a new component while an AA battery set is used to replace the 6v battery.

Participants

There were 20 participants: 10 male and 10 female, with an average age of 27 (SD=5.61, range 19 - 41 years old). We recruited participants who have their waist size larger than 60 cm (i.e. 24 inches) so that the size allowed for an inter-actuator distance larger than 4 cm (i.e. the two-point threshold for the waist area) which in turn assures point localisation and distinguishability. Participants' average waist size was 79 cm (SD=12, range 61 - 99 cm). On average, they indicated that they have lived in Bath for 2.4 years (SD=1.7, range 0.17 – 6 years). All participants had never experienced tactile navigation displays in actual environments. All reported no irregularity with tactile stimulation around their waist at the time of the study. Results from pre-test questionnaires indicated that all participants understood the concept of egocentric directions and landmarks and had no difficulties identifying them. Each of them received a 10 pounds monetary incentive at the end of the experiment.

Tactile stimuli

There were three types of spatial signals: direction, landmark and destination signals. Simplified versions of the belt illustration are used in this subsection (as seen in Figures 6.2 – 6.5); some of the actuators have been removed to emphasise the stimulated actuator(s).

Direction stimuli

The eight egocentric directions represented are the same as in all of our previous studies (see Table 4.3 for the mapping between the actuator number and the direction represented and Figure 4.4 and 4.12 for illustration of directions). During the walking sessions, each directional signal was given twice with a two-second gap in both condition SS and LM.

As described earlier in Section 5.4.1, this particular study aimed to evaluate the effect of the *straight* signal on the ability to recall landmarks on routes. As a result, for condition SS, we assigned two meanings to this *straight* signal that it signifies a wayfinding instruction and a confirmation of a landmark. This assignment replicated the multiple roles of spatial information in the real world. For example, with visual navigation, landmarks can have two roles: identify decision and destination points; or serve as confirmation cues (see Section 2.1.3 and Appendix A2.5).

In summary, for each *straight* signal (Figure 5.2):

- Indicated both a direction and a confirmation of a landmark in condition SS;
- Indicated a direction in condition LM.

We made sure that participants clearly understood a composite meaning of the signal prior to the walking session.

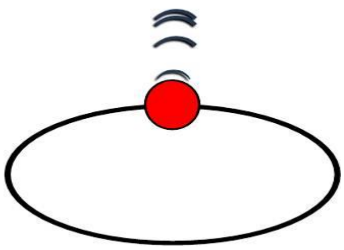

Figure 5.2 A straight signal, vibration being generated on the front centre actuator (number 3).

Landmark stimuli

We used the dual-actuator technique to generate landmark signals (see Section 4.4.5). Namely, vibration patterns were the same for all landmarks but different pairs of actuators would represent different landmarks (see an example in Figure 5.3). Results from the experiments reported in Chapter 4 suggested that the horizontal and vertical actuator pairs afforded good performance. These pairs include the 2-4, 1-5, 6-8, 2-8, 3-7 and 4-6 (see the reference of actuator number in Figure 4.20). As we chose to represent seven landmarks, we also used the 3-8 pair which was the next best pair according to the experimental results (see Table 4.12). For the set of landmarks, we drew on the same list derived and used in Chapter 4.

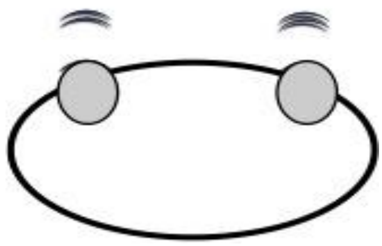

Figure 5.3 An example of a landmark signal generated on actuator pairs 2-4.

A destination cue and a set of landmark signals

During the experiment there were two types of landmarks being displayed by the system, *on-route* and *destination* landmarks. Notifications for each *on-route* and *destination* landmarks were being given as a set of two and three signals respectively. A two-second pause was introduced as a gap that separates one signal type from the next.

For any *on-route* landmark, a set of two signals comprised of the landmark signal and its location in relation to the wearer's heading direction was given. An example of a set of on-route landmarks is demonstrated in Figure 5.4. For this particular example, the signal's meaning is that there is a specific landmark on your left (landmark category varies depending on the signal 2-4's meaning association).

Figure 5.4 A signal set for an on-route landmark comprises of two signals: (1) the landmark and (2) its location in relation to the wearer's heading.

For any destination landmark, a set of three signals comprised of a destination notification (that a destination has been reached), the landmark signal and its location in relation to the wearer's heading direction. A destination notification signal was given by simultaneously vibrating all eight actuators. An example of a set of destination landmarks is demonstrated in Figure 5.5.

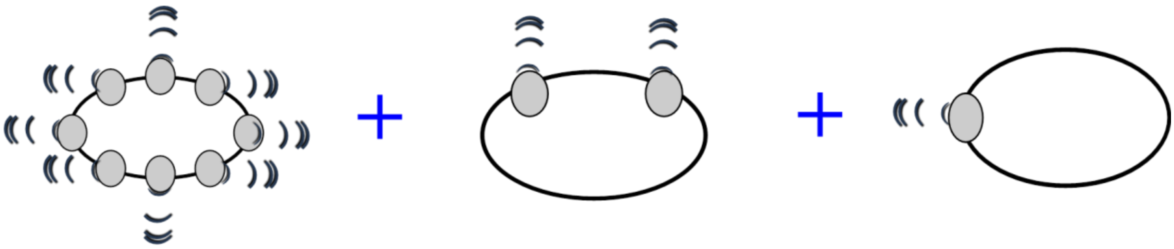

Figure 5.5 A signal set for a destination landmark comprises of three signals: (1) a destination notification, (2) a landmark, and (3) its direction. In the figure, it means "you have reached the destination" + "there is a specific type of landmark" + "on your left".

Walking scenarios and signal timing

In order for participants to navigate to a destination, there were three walking scenarios that they would encounter. Scenarios included (1) reaching a decision point, (2) passing a landmark and (3) reaching a destination. The following subsections demonstrate how signals were being delivered in each scenario in both conditions.

Scenario 1 – Reaching a decision point

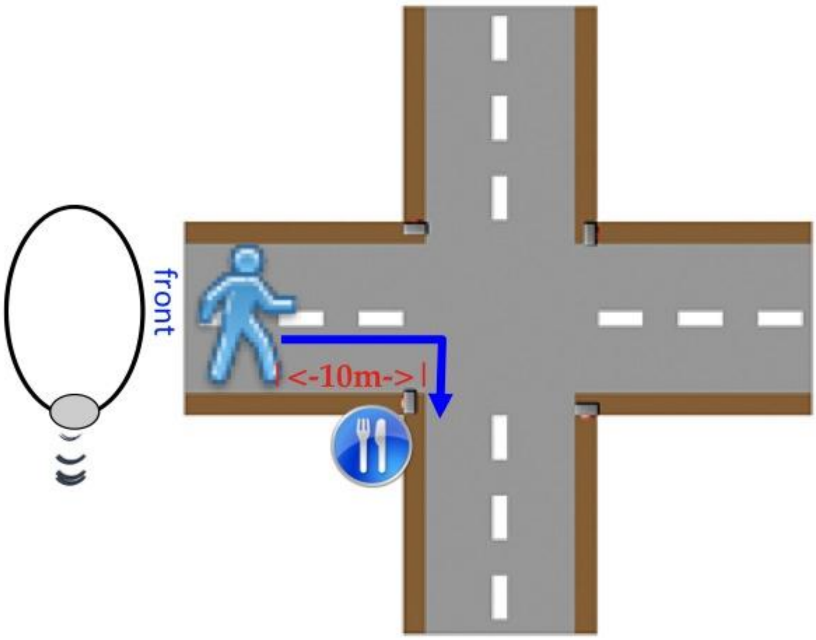

Figure 5.6 An example for Scenario 1: Reaching a simple decision point

In this example, the navigator will be instructed to turn right at the upcoming decision point in both experimental conditions. Upon approaching[67] such a decision point, the system generates a directional signal, a *right* signal two times with a 2-second gap between them.

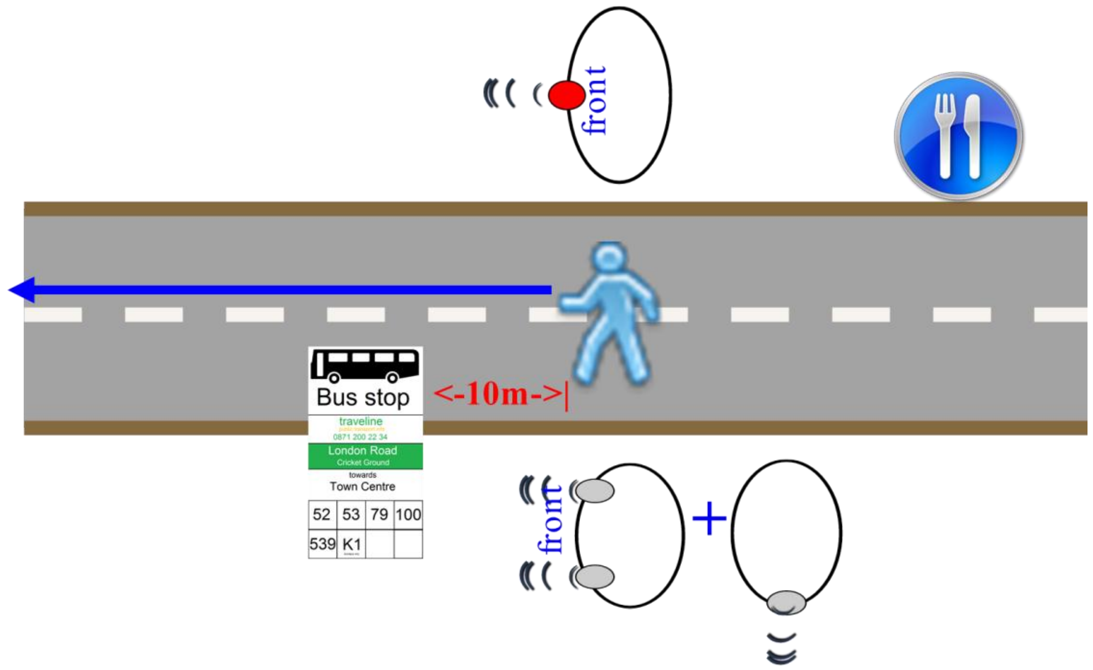

Figure 5.7 An example for Scenario 2: Walking a long segment (top part for condition SS, bottom part for condition LM)

Scenario 2 – Passing a landmark

Figure 5.7 demonstrates how signals would be displayed when passing a landmark: the top part for condition SS and the bottom part for condition LM. Please note that the different types of spatial signals in both conditions were aimed to be used as a confirmation for the navigator that they are on the right path by informing them of passing important landmarks. In this example, there are two landmarks along the route, a bus stop and a restaurant. In the actual environment, the route may contain a number of potentially important landmarks but only some of them will be used as references during navigation. This scenario reflects the reality that only the bus stop (i.e. public transportation) is being used. For condition SS (Figure 5.7 top): upon approaching *the bus stop*, the system generates a *straight* signal twice with a two-second gap, indicating that the navigator is on the correct path because they are approaching a landmark that is located on the planned route. For condition LM (Figure 5.7 bottom): upon approaching the *bus stop*, the system

[67] Approximately 10 - 20 meters pending the navigator's walking speed.

generates (1) a *public transportation* signal, pauses for two seconds, and (2) a *left* signal, indicating that the navigator is on the correct path because there is a bus stop on their left.

Scenario 3 – Reaching a destination

In this scenario, the navigator will be notified with the same set of signals in both conditions that they are about to reach a destination. In this example (Figure 5.8), upon approaching the *destination*, the system generates (1) a *destination* cue, a two-second pause, (2) a *tourist attraction* signal, a two-second pause, and (3) a *right* signal, indicating that they are reaching their destination, an attraction, which is on their right.

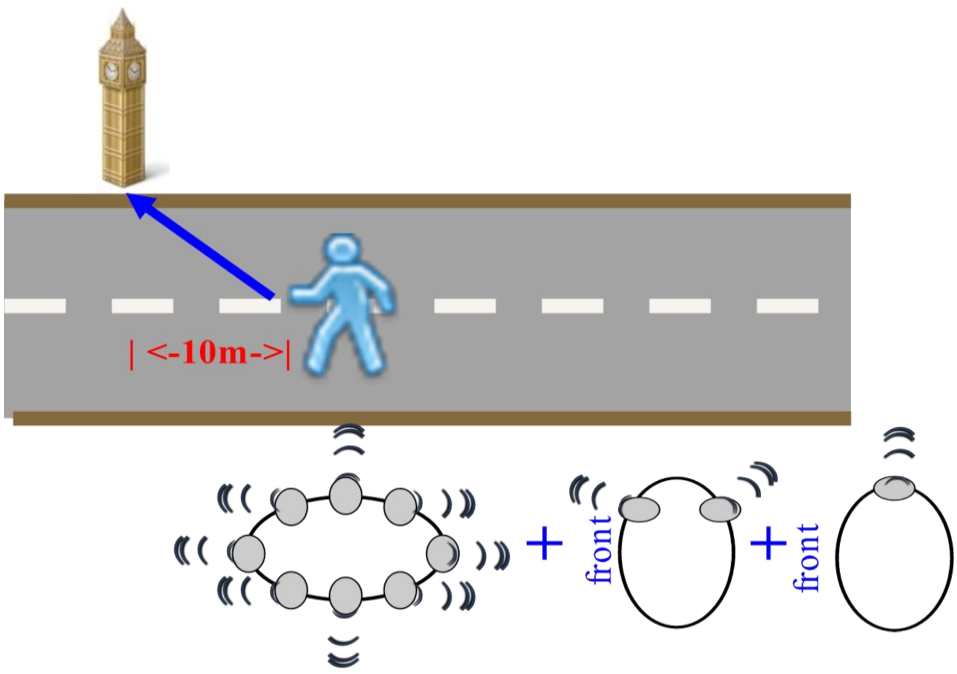

Figure 5.8 An example for scenario 3: Reaching a destination

5.4.3 Procedures

Experimental conditions and procedures

An overview of the experimental conditions is demonstrated earlier in Tables 6.1 (training) and 6.2 (walking). Each participant must pass two training sessions with 100% accuracy performance and run both walking conditions.

Training stage – measuring learnability and memorability

Following the same training practice reported in Chapter 4, participants carried out a 4-phase training[68] exercise to learn and memorise signal associations for all signal types, i.e. direction, destination and landmarks. Half of the participants were allowed to look at the visual diagram, which illustrated the stimulated actuators with their landmark meaning association, for two minutes. Training stopped when they achieved 100% accuracy performance in both training sessions, i.e. T1 and T2. At the end of each training session, participants were asked to rate the level of cognitive workload required. Landmark meaning associations and order of appearance were systematically randomised across participants to prevent any bias on any particular pair of actuators or landmark type.

For the training stage, there was one independent variable: the presence or the absence of a visual diagram. Dependent variables included training effort (including training rounds, duration and number of training signals) and cognitive workload requirements (using NASA TLX).

Walking stage – measuring navigation performance, confidence, perceived usefulness and the ability to recall routes

For the walking part, there was one independent variable: the type of cues being either *straight* or *landmarks* signals. Dependent variables included navigation performance (including navigation duration, accuracy in direction and landmark identification, error and breakdown[69]), level of confidence (subjective scores on a 1-5 likert scale), level of perceived usefulness (using TAM), and the ability to recall routes (drawing). Additionally, we collected information on cognitive workload required, user preferences, tactile navigation process and other practical issues through questionnaires and interviews conducted after the experiment.

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[68] The 4-phase training exercise comprises of the display, memorise, trial and test phases. For more information, please refer to Section 4.4.6 Procedures / Experimental Procedures / Training .

[69] According to Winograd & Flores (1986), a computer system is meant to be used in a *transparent* fashion to help users complete their tasks. Any situation in which something has gone wrong resulting in users switching their attention from intended tasks to the system in order to solve problems is referred to as *breakdown* (Winograd & Flores, 1986). *Breakdown* includes, for example, failing to notice changes in displayed information and users unable to find an undo function. For this particular study, *breakdown* refers to the following: (1) a number of occasions failing to perceive tactile signals (both directions and landmarks), (2) a number of occasions failing to interpret both types of tactile signals, (3) a number of occassions reporting confusion at any point on route, (4) a number of occasions hesitating to make decision at each manoeuvre, and (5) a number of occasions hesitating to identify landmarks.

Each participant carried out both conditions by navigating two different pre-determined routes[70] because navigation tasks are sensitive to repetition (Goodman et al., 2004). Both routes were of the same 800-metre length, which required 11 minutes walking[71]. Each route contained the same number of decision points and the same seven types of landmarks (see Appendix 5). The order of conditions was counterbalanced. Namely, all participants started the walk with route 1; half of the participants walked condition SS while the other half walked condition LM with this route. We have increased the length of all vibration signals from 1.2 to 2 seconds to compensate participants' movement effect on vibration perception.

The system was fitted carefully. Participants were informed that the system would help them navigate to reach an unfamiliar destination. Before embarking on the journeys, all participants demonstrated that they could remember all signal associations correctly. At the starting point, participants were oriented toward an intended heading direction. Once participants started walking, the system compared participants' current GPS location with pre-determined route points and triggered appropriate cues. Specifically, at decision or destination points, the system triggered a set of directional cues or a set of destination landmarks respectively. For landmark cues, upon approaching each pre-defined landmark, the system either generated a set of *landmark* signals in the LM condition or a set of *straight* signals in the SS condition. Each signal set was presented only once. When each signal set has been generated, participants were required to indicate (as "quickly and accurately" as they could) to which direction or landmark they thought it corresponded, by speaking out loud or making an actual turn (in case it was a directional signal at a decision point). Landmark stimuli appeared in a different order from that of the training sessions.

Additionally, participants were encouraged to speak out loud about any relevant information such as perceived environments, their understanding of signals, their decisions and anything that came to mind during the course of navigation. Data was gathered using both system logs and verbal protocols. The experimenter walked along and made sure that

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[70] See Appendix 5

[71] According to an estimation by Google Maps, courtesy of Google Inc.

all relevant data of the whole journey was being recorded (using an application Audacity[72]).

At the end of each route, participants were asked to (1) rate confidence, workload, and perceived usefulness scores; (2) complete questionnaires (open-ended questions); and (3) draw the route taken. Once they completed both routes, participants were asked to (1) rate preference and attitude; (2) discuss the system's practicality; and (3) perform an activity-card arrangement[73].

Prior to the experiment, we measured participants' normal walking speed which was 4.27 km/hr on average. This information will be used for subsequent data analysis in comparison with percentage preferred walking speed (PPWS)[74] (Goodman et al., 2004).

In the previous field study reported in Chapter 3, some of our participants suffered from GPS signal shortage. For the experiment designed in this study, we have carefully surveyed and chosen the routes as well as modified the system so that it can cope with such issues and delivered timely signals at the intended decision points.

The whole experiment took place over 3 weeks. The walking part was carried out in similar environmental settings across participants, for example being the same time of the day, and in good weather conditions. Some weather variation was acceptable given mild weather that did not obstruct navigation.

The total experimental duration for each participant was one hour, being 15 minutes for two separated training sessions and 45 minutes for the walking sessions that included navigating two routes and other tasks such as answering questionnaires.

Hypotheses

For learnability, in addition to the improvement of image quality[75] (Edworthy & Hards, 1999), we provided a visual illustration of the stimulated actuators and their associations to half of the participants. We hypothesised that:

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[72] Audacity is an open-source, cross-platform software for recording and editing sounds (Source: http://audacity.sourceforge.net/). At the time of the study (2011), we used Audacity 2.0.

[73] The card-sorting was expected to allow us to understand the tactile pedestrian navigation process.

[74] See Glossary.

[75] By increasing labels' font size, improving picture quality as well as adjusting their layout

H1 – Participants who were given a visual diagram would spend less time and effort to achieve the same level of performance than participants who were not given a diagram.

As it was fundamental that all participants must remember all signal patterns prior to the actual field comparative study, we have designed the experiment that they must attend and pass two training sessions, T1 and T2, which were scheduled several days apart. Learning with improved mnemonics, we did expect that participants would be able to remember all landmark signals very well after passing T1. On that account, we hypothesised that:

H2 – Participants would need to make significantly less effort to achieve the same level of performance in session T2 than in session T1.

Our field study compared the two types of spatial information which can be used as confirmation cues for landmarks. During the walking sessions, both types of signals were given to participants in two different conditions (Table 5.2) at the exact same location where important landmarks are situated. Although there was no evidence to prove that either the *straight* signal or the *landmark* signal is more effective than one another, we did expect that specific *landmark* signals would provide users with precise information hence increasing navigation performance and confidence, thereby increasing the system's perceived usefulness. This assumption led to our prediction:

H3 – Participants would perform significantly better in condition LM than in condition SS.

H4 – Participants' confidence[76] would be significantly higher in condition LM than in condition SS.

H5 – Participants would perceive the system that provided both direction and landmark signals (condition LM) as more useful[77] than the system that only provided directional information (condition SS).

As we also aimed to investigate the system's practicality, there were other measurements including route completion time, user preference and level of cognitive effort required

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[76] The degree to which participants believe that they could rely on the system during the course of navigation.

[77] Participants were asked to rate each system's perceived usefulness score, which is the degree to which participants perceive the system as helpful and practical for their navigation.

during both training and walking sessions. We were also eager to learn about pedestrians' navigation process using a tactile navigation system.

5.4.4 Results

In this section, we report experimental results from both training and walking stages.

Learnability

Data gathered from training was used to analyse signals' learnability. Descriptive statistics shown in Table 5.3 demonstrate effort required to learn three[78] different signal types by all participants. In each training session, participants spent the most effort to learn landmarks and the least to learn a destination cue. These results were consistent with those reported in the previous chapter.

Table 5.3 Average training requirements for different types of signals

Measures	Direction		Destination		Landmark	
	T1	T2	T1	T2	T1	T2
Number of rounds	4.50	2.56	3.40	2.10	5.00	3.00
Number of signals	35.20	19.10	3.40	2.10	45.75	23.15
Time (min:sec)	02:04	01:11	00:40	00:16	03:26	01:25
Response time[79] per signal	00:03	00:02	00:03	00:02	00:04	00:03

In the previous experiment reported in Chapter 4 on learning landmarks (see category *Landmark-dual* in Figure 4.13), an average participant carried out 6.85 training rounds and spent 04:14 minutes trying 95 signals. By using only the vertical and horizontal actuator pairs to represent landmarks in this study, we have seen learning improvement; on average participants carried out 5 rounds and spent 03:26 minutes trying 46 signals.

We then broke down participants into two groups, one with and one without a visual diagram. T1's results (in Figure 5.9) showed that overall training requirements for participants without a visual diagram were higher than those with a diagram. Statistically, an independent-samples t-test showed significant differences between the two groups of participants in number of rounds, $t(18) = -3.12$, $p < 0.05$, and training duration $t(18) = 7.79$, $p < 0.05$. However, no significant difference was found in number of training signals, $t(18) = -2.51$, $p > 0.05$).

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[78] There were eight directions, one destination and seven landmarks to learn.

[79] Response time refers to the onset of the stimulus to the onset of the response, including movement time.

Table 5.4 presents statistical data of training requirements for each training phase by the two groups of participants. An independent-samples t-test indicated that the amount of training requirements was significantly affected by the presence of a visual diagram, in most cases. Generally, participants who were given a visual diagram spent less time and effort to achieve the same level of performance as participants who were not given a diagram. In other words, a visual diagram helped improve learnability of landmark signal associations. Hence, we accepted *H1*.

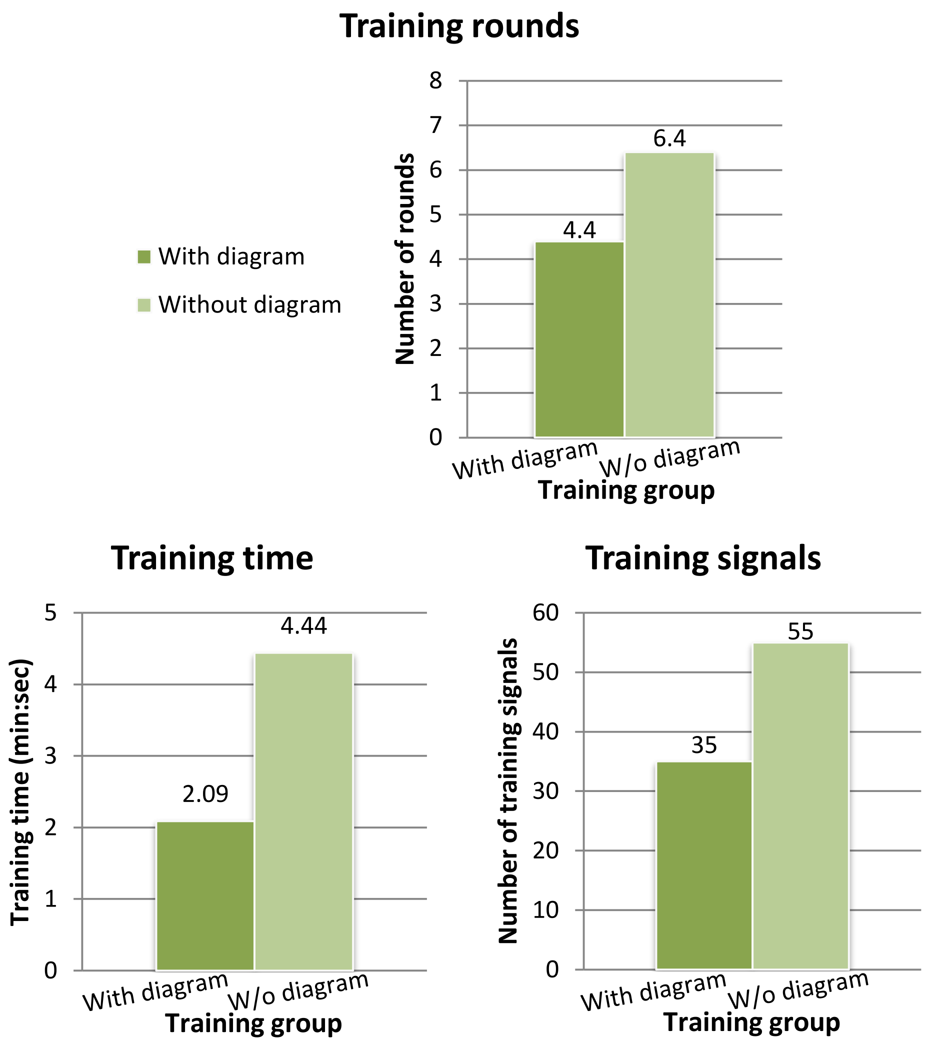

Figure 5.9 Training effort requirements of the two training groups in T1

Table 5.4 Independent-samples t-test result for training requirements: * indicates that the result is significantly affected by the presence of a visual diagram t(18), $p < 0.05$.

Training phase	No of rounds	Duration	No of signals
Phase 1	3.58	6.87*	3.58
Phase 2	-0.43*	3.04	1.95*
Phase 3	1.24*	3.27	1.50*
Phase 4	2.69*	13.37*	2.25*

Once participants had learned landmark signal associations in T1, the presence of a visual diagram did not seem to affect performance in T2. An independent-samples t-test found no significant difference between the two groups of participants in number of training rounds, duration and number of training signals (all $p > 0.05$).

At the end of each training session, we asked participants to rate subjective cognitive workload required to complete their tasks using a NASA TLX. Between the two groups of participants, significant differences were found on performance (T1: $t(18) = -1.47$, T2: $t(18) = -2.09$, both $p < 0.05$) and frustration (T1: $t(18) = -2.94$, T2: $t(18) = -2.71$, both $p < 0.05$). Namely, the group that studied a visual diagram felt they performed better and felt less frustrated than the group without a diagram. No significant difference on the other four task load measures[80] was found ($p > 0.05$ in each case). For the detailed TLX scores, please see Appendix 6.1.

For both training sessions, there was no significant difference found in all measures between male and female participants (all $p > 0.05$).

Memorability

Results of the three measurements revealed the same pattern for memorability of direction, landmark and destination signals. Specifically, it took a significantly fewer number of rounds, shorter duration and fewer number of signals to achieve 100% performance in T2 than in T1 (all $p < 0.002$). Between two training sessions, participants generally spent 50% less time, 50% fewer number of signals and 40% fewer number of rounds in T2. There was no significant difference in response time in all cases (all $p > 0.05$).

[80] The other four task load measures are mental demand, physical demand, temporal demand and effort.

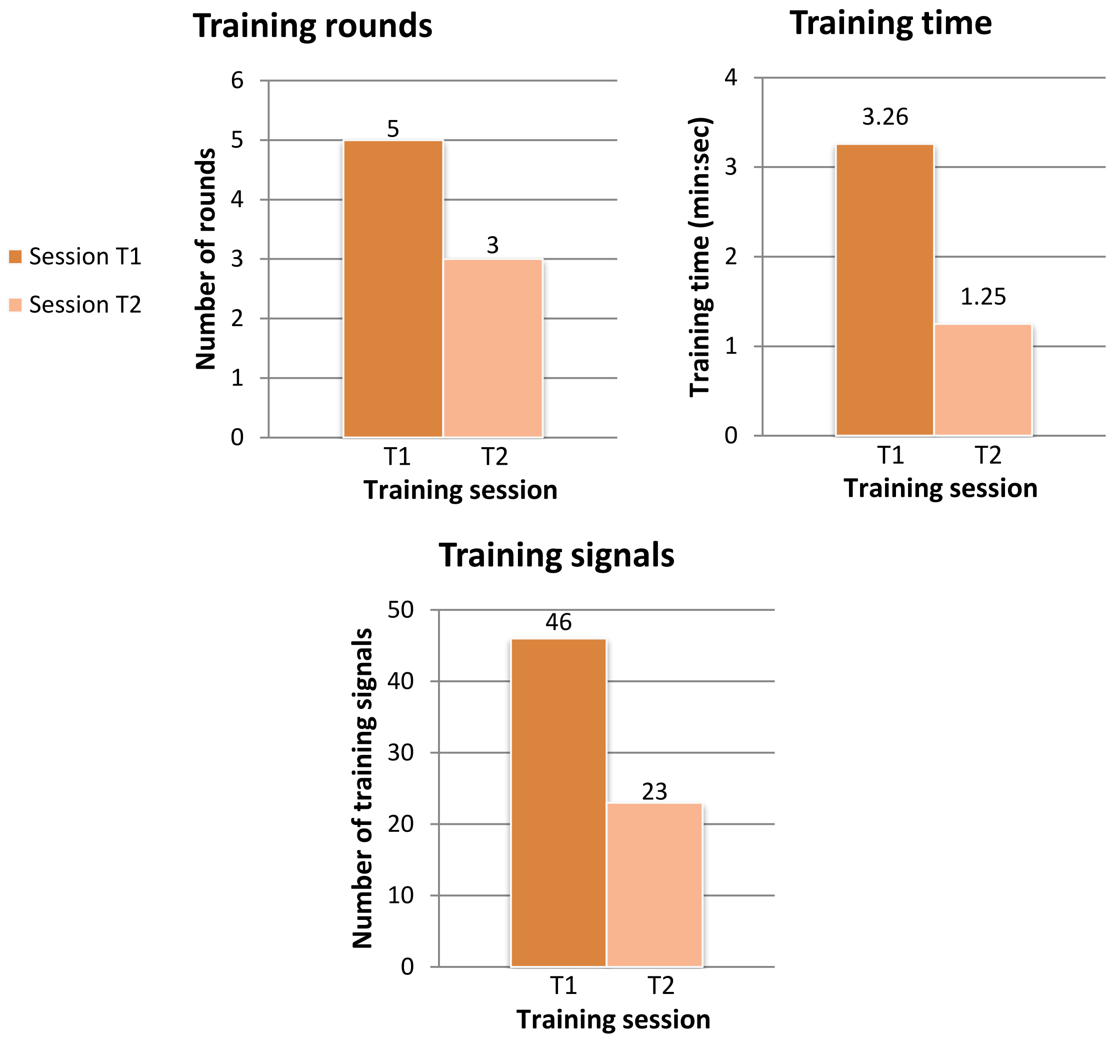

Figure 5.10 Training effort requirements of the two training sessions

As we had participants learning landmark signals with improved mnemonics, we expected they would spend less time and effort in T2 to achieve the same level of performance as in T1. As shown in Table 5.3 and demonstrated below in Figure 5.10, a paired-samples t-test revealed that participants carried out significantly fewer number of rounds ($t(19) = 3.56$, $p < 0.002$), shorter duration ($t(19) = 3.55$, $p < 0.002$), and fewer number of signals ($t(19) = 4.85$, $p < 0.002$) in T2 than in T1. Hence, we accepted *H2*.

For the landmark part, detailed analysis revealed that participants seemed to perform best with the farthest vertical (3-7) and horizontal (1-5) pairs than with other pairs. Initially we expected that the 2-8 pair would afford high performance. In fact, participants made most mistakes with signal 2-8 in session T1. We assumed that this low performance might be caused by the use of the 3-8 pair which was not uniquely different from the 2-8 pair. However, the error did not occur in T2.

For the task load analysis of the two training sessions, a paired-samples t-test revealed that the two training sessions required a significant difference level for task loads: mental demand ($t(19) = 5.55$, $p < 0.002$), temporal demand ($t(19) = 3.30$, $p < 0.05$) and effort ($t(19) = 4.82$, $p < 0.002$). In other words, participants found it less cognitively demanding to achieve the same level of performance in T2 than in T1. There was no significant difference on physical demand, frustration and performance (all $p > 0.05$)[81].

We took an opportunity to compare the subjective workload scores between male and female participants in both training sessions. An independent-samples t-test revealed that a significant difference was found on frustration (T1: $t(18) = 1.72$, T2: $t(18) = 1.57$, both $p < 0.05$). Namely, male participants reported a significantly higher level of frustration than female users. No significant difference was found on the other five task load measures ($p > 0.05$ in each case)[82].

Navigation performance

Figure 5.11 demonstrates the means of accuracy, breakdown, error[83] and time performance of the two walking conditions.

To analyse navigation performance, we ran a paired-samples t-test of the two walking conditions. On walking duration, participants spent a slightly longer duration to complete the route in condition LM than in condition SS. Nevertheless, there was no significant difference between the two conditions ($t(19) = 2.03$, $p > 0.05$). On performance, there was no significant difference between the two conditions on accuracy ($t(19) = -1.54$) and breakdown ($t(19) = 0.64$), both $p > 0.05$. A significant difference was found on error ($t(19) = -2.48$, $p < 0.05$). Specifically, participants made significantly fewer number of errors in condition SS than LM. Based on our interpretation of these results, we concluded that participants performed equally well in both conditions. Hence, we rejected *H3*.

[81] For the detailed TLX scores, please see Appendix 6.2.

[82] For the detailed TLX scores, please see Appendix 6.3.

[83] Error refers to incorrect localisation of signals and incorrect identification of landmarks.

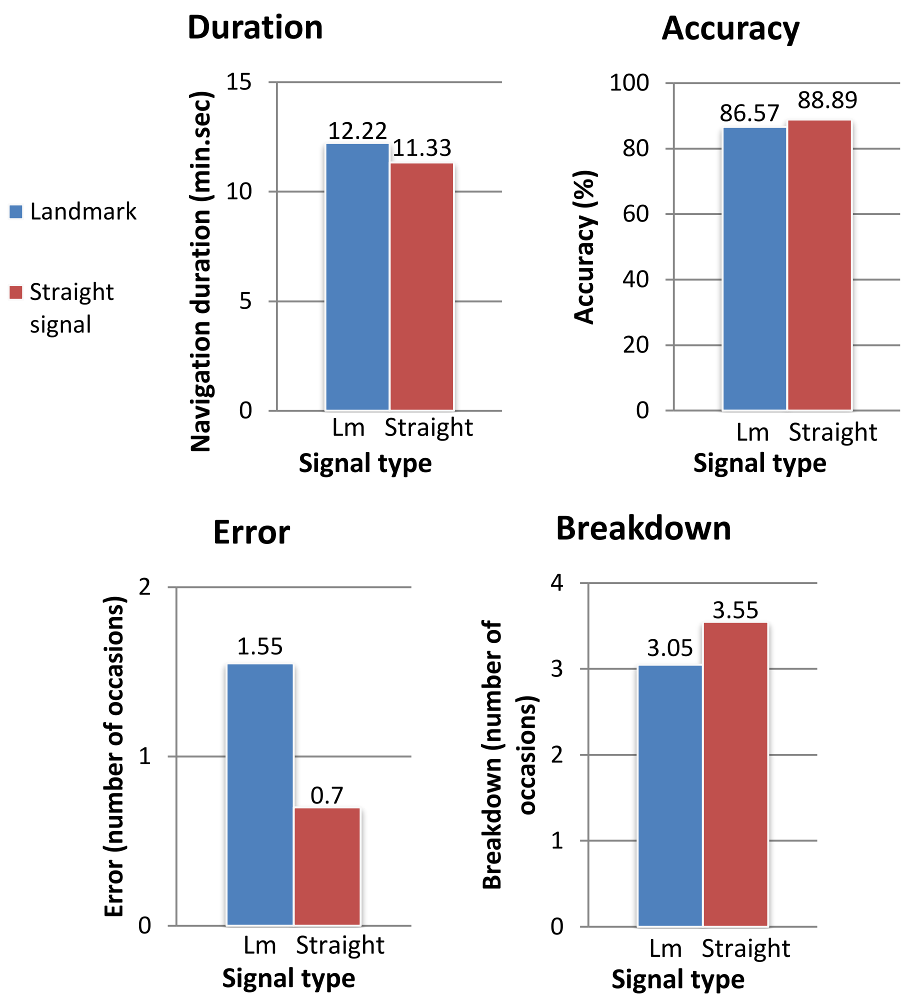

Figure 5.11 Mean navigation duration, accuracy, error and breakdown: time in mm.ss; accuracy in %; error and breakdown in number of occasions.

Table 5.5 shows additional detailed data including PPWS[84], detailed accuracy performance (on identification of direction and landmark), overall and detailed and breakdown[85].

We broke down accuracy data into the level of information types (Table 5.5, 2nd and 3rd rows) and performed further analysis using a paired-samples t-test. No significant difference was found on accuracy performance between the two conditions both on direction and landmark identification (all $p > 0.05$).

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84 See Glossary.

85 Breakdown comprises of four elements: (1) failing to perceive – system generated signals but participants reported not sensing them, (2) failing to identify – participants reported sensing signals but chose not to identify them, (3) failing to distinguish – participants interpret direction as landmarks and vice versa, and (4) hesitating to identify – participants reported sensing signals and took longer than five seconds to identify them. Please note that the five-second threshold was based on the average response time from the two lab training sessions (see Table 5.3).

Table 5.5 Navigation performance (* indicates significant difference between the two conditions)

No	Measurements	Condition SS	Condition LM
1	PPWS (km/hr)	4.17	4.00
2	Accuracy *Landmark* (%)	64.29	76.19
3	Accuracy *Direction* (%)	97.73	93.18
4	Breakdown - *Overall* (number of occasions)	3.55	3.05
	Failing to perceive	0.10	0.25
	Failing to identify	2.20	0.20
	Failing to distinguish	0.00	0.65
	Hesitating to identify	1.25	1.95
5	Breakdown - *Landmark* (number of occasions)	2.80	2.40
	Failing to perceive	0.00	0.10
	Failing to identify*	2.20	0.20
	Failing to distinguish*	0.00	0.55
	Hesitating to identify*	0.60	1.55
6	Breakdown - *Direction* (number of occasions)	0.73	0.66
	Failing to perceive	0.08	0.08
	Failing to identify	0.00	0.00
	Failing to distinguish	0.00	0.08
	Hesitating to identify	0.65	0.40

As this experiment emphasised landmark signals' recognition, we looked further into breakdown data. At the overall level (considering all four types of breakdown incidents from the trigger of both direction and landmark signals – Table 5.5 4th row), there was no significant difference (as reported earlier)[86]. However, when we looked closely at the detail of breakdown rate of landmark identification (Table 5.5 5th row), we found interesting insights as follows:

- Participants had a significantly greater number of occasions failing to identify landmarks in condition SS than in LM ($t(19) = 4.02$, $p < 0.002$);
- Participants had significantly more problems in distinguishing landmark from direction signals in condition LM than in SS ($t(19) = -2.46$, $p < 0.05$);
- Participants showed significantly more sign of hesitation in condition LM than in SS ($t(19) = -2.83$, $p < 0.05$);
- No significant difference was found on the ability to perceive landmark signals in both conditions ($t(19) = -1.45$, $p > 0.05$).

Based on the above detailed analysis, in the condition where landmark signals were given together with direction signals (condition LM), there were higher rates for distinguishability and hesitation. On the other hand, in condition SS where only direction signals were given, participants did not have hesitation on landmark identification because

[86] In addition, no significant difference was found at the detail of breakdown rate of direction.

they simply skipped it. All four types of breakdown incidents compensate each other. As a result, the overall breakdown rate was not significant.

We further examined whether there was an effect of a visual diagram on accuracy of performance in condition LM. Using an independent-samples t-test, we found no significant difference between the two groups of participants ($t(18) = -0.38$, $p > 0.05$). In other words, the diagram made no difference at this stage of the study. Every participant managed to remember all landmarks before the actual walking started and performed equally well. Despite being able to remember all landmarks, during the actual walking session they had failed to identify or incorrectly identify landmarks (see Figure 5.12). We inferred that the reduction of vibration detection and landmark identification were affected by mobility and environmental dynamics such as visual workload.

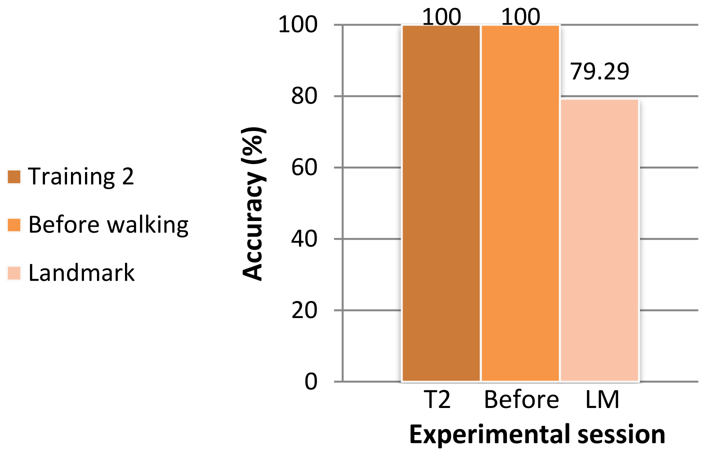

Figure 5.12 Side-by-side comparison of means accuracy (%) of training session T2, the test prior to the actual walking and condition LM

We took an opportunity to compare the subjective workload scores between male and female participants in both walking conditions. An independent-samples t-test revealed that a significant difference was found on mental (SS: $t(18) = 1.12$, LM: $t(18) = 0.39$, both $p < 0.05$) and physical demand (SS: $t(18) = 0.78$, LM: $t(18) = 1.37$, both $p < 0.05$). Namely, male participants reported a significantly higher level of mental and physical demand than female users. No significant difference was found on the other four task load measures ($p > 0.05$ in each case)[87].

[87] For the detailed TLX scores, please see Appendix 6.3.

Confidence

After each walking condition, post-questionnaires were used to gather users' subjective data on the two different types of tactile signals being used for landmark identification. These subjective measures included: confidence scores, ease of landmark identification and system reliability (see Table 5.6). Participants gave rating on a 1-5 likert scale, 1 being low and 5 being high.

Table 5.6 Subjective mean scores of confidence, signal identification and system reliability (likert scale 1-5, 1 being low and 5 being high; *indicates significant difference at $p < 0.05$ between the two conditions).

No	Measurements	Condition SS	Condition LM	Statistical data, t(19)
1	Confidence*	4.10	3.45	2.29
2	Ease of landmark identification	3.15	3.15	0.00
3	System reliability	3.95	3.80	0.77

A paired-samples t-test was used to analyse raw data (shown in Table 5.6). In general, participants thought that it was neither easy nor difficult to identify the actual landmarks in the environment from both types of tactile signals. Nonetheless, they felt significantly more confident with walking condition SS than LM. This contradicted our initial expectation. Therefore, we rejected *H4*.

Perceived usefulness

Table 5.7 Subjective mean scores of TAM's perceived usefulness and perceived ease of use, TAM scale 1-7, 1 being strongly agree and 7 being strongly disagree; *indicates significant difference at $p < 0.05$ between the two conditions.

		Mean scores		Statistical
No	Measurements	Condition SS	Condition LM	data (t_{19})
1	Perceived usefulness			
	Navigate more quickly*	2.25	3.00	-3.68
	Increase navigation performance*	2.35	2.95	-2.11
	Easier navigation*	2.20	2.95	-2.88
	Useful*	2.15	2.75	-3.04
2	Perceived ease of use			
	Easier to learn*	2.15	2.55	-2.18
	Easier to become skillful*	2.10	2.80	-2.90
	Clear and understandable	2.35	2.35	0.00
	Ease of use	2.20	2.40	-1.45

In order to measure users' likelihood in accepting the tactile navigation system, we asked participants to rate the system's perceived usefulness after each walking condition using the modified TAM (see Appendix 3). Table 5.7 demonstrates means and statistical (a paired-samples t-test) values of perceived usefulness and perceived ease of use (see Section 5.3.1 for explanation) of the two walking conditions.

Condition LM scored significantly lower than condition SS in all of the perceived usefulness and two of the perceived ease of use measures. As these results contradicted our hypothesis on perceived usefulness, we rejected *H5*.

Tactile navigation process

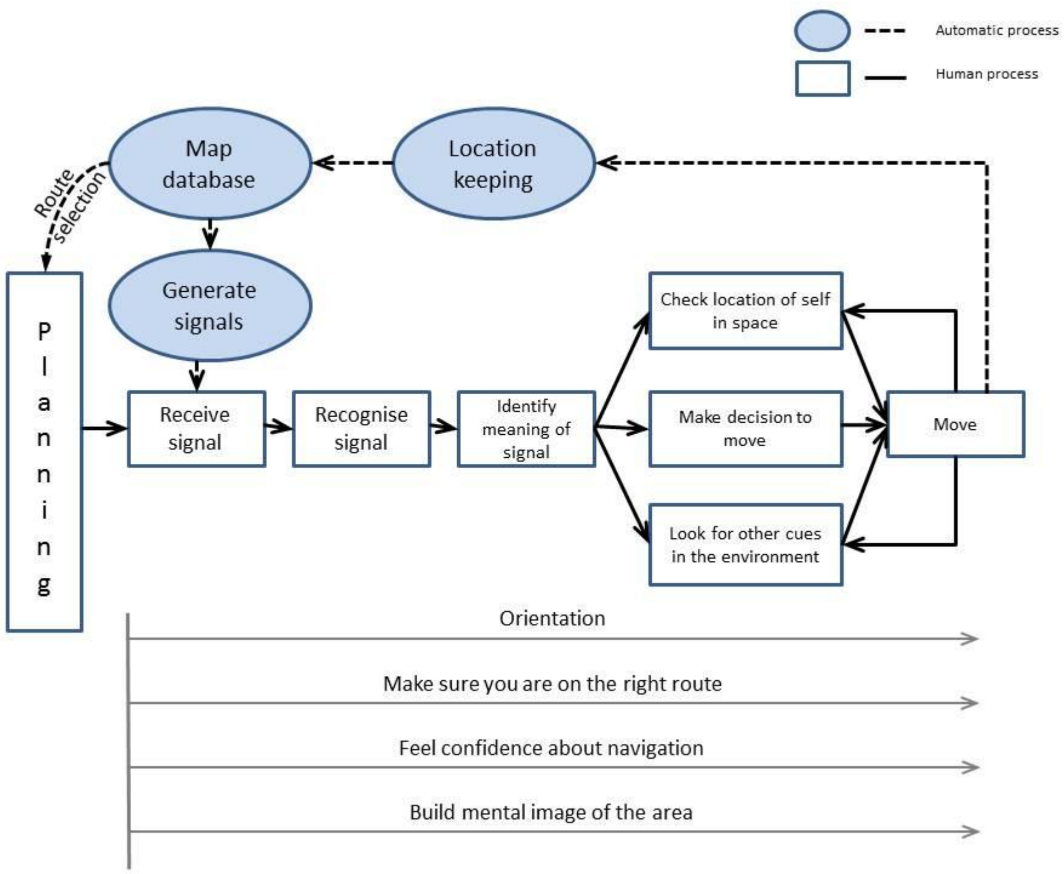

Figure 5.13 Tactile Navigation Process

At the end of both journeys, we asked participants to arrange activity cards[88] that reflected their navigation process. Participants provided slightly different accounts of their navigation process that allowed us to synthesise these data and come up with a preliminary version of a tactile navigation process demonstrated in Figure 5.13.

[88] There are 12 activity cards: plan route, receive tactile signal, recognise tactile signal, identify meaning, make decision to move, move, orientate yourself, check location of self within space, look for other cues, make sure you are on the right route, feel confidence in navigation and build a mental image of the area.

Other results

Preference

11 participants (55%) preferred the system generating straight signals to landmark signals. This outcome has not been affected by the order effect. Namely, participants did not indicate their preference based on the order of condition experienced first. Instead, participants chose their preferred system based on their provision of navigation purposes, being questing or exploring.

Difficulty to distinguish signals in the field

Participants reported a moderately higher level of difficulty to distinguish direction from landmark signals in the field (condition LM) than in the lab. On a 5-point likert scale, when 1 is more difficult and 5 is less difficult, mean score of difficulty was 2.55 (SD=1.10).

The majority of participants suffered from the movement effect as they reported that the sensation seemed to be less strong when they started moving. These drawbacks led to signal ambiguity and a number of errors and breakdowns. A number of participants suggested stronger vibration.

Effect of physical landmarks on felt vibration

According to our observation, 'distance to landmark' may contribute to the ability to identify landmarks with no hesitation in both conditions. Participants reported a moderately high level of effect of physical landmarks on their felt vibration, on a 5-point likert scale, when 1 is low and 5 is high, the mean effect was 3.7 (SD=0.66).

Other practicality issues

During the experiment, there was one participant who reported one false positive[89] incident in condition LM. Another two participants paused during their walk whenever they received landmark signals, trying to recall the landmark associations and refused to look for the cues in the environment. However, we took these two incidents as a minor effect of having run an experiment in the field and it did not impede the overall results.

[89] False positive refers to the occasion when participants reported perceiving signals when none were actually generated.

5.4.5 Discussion

The effect of gender on TactNav's accuracy performance

We have reported earlier that in the training sessions, there was no significant difference in terms of learnability and memorability between two genders. In this subsection, we would like to further exhibit that gender difference has very little or no effect on tactile navigation performance. We ran an independent-samples t-test on performance data of the two walking conditions.

On *accuracy performance*, there was no significant difference between male and female participants in both conditions: SS: $t(18) = -1.57$, LM: $t(18) = -1.77$, both $p > 0.05$. On *error*, there was no significant difference between male and female participants in both conditions, SS: $t(18) = 1.00$, LM: $t(18) = 0.50$, both $p > 0.05$.

On *breakdown*, a significant difference was not found between male and female participants in condition SS at the overall level ($t(18) = 2.33$, $p > 0.05$) and at all detail levels, all $p > 0.05$. However, in condition LM, a significant difference was found between male and female participants at the overall breakdown rate ($t(18) = 1.70$, $p < 0.05$). Looking at the detailed levels, male participants significantly failed to perceive ($t(18) = 1.50$, $p < 0.002$) and failed to identify ($t(18) = 1.81$, $p < 0.002$) signals on more occasions than female participants. Both genders made equal numbers of failing to distinguish signals and hesitation ($p > 0.05$).

In summary, it was found that gender has an effect on *breakdown* but has no effect on *accuracy performance* and *error*.

Results from all of our empirical studies reported in this and previous chapters have been consistent that men and women can navigate almost equally well using tactile navigation displays. Our results were also congruent with that of Karuei et al.'s (2011).

The effect of wearable technology on walking speed

We have reported earlier in the *practicality issues* subsection that there were some participants who spent a considerably long time to identify landmarks at some decision points in condition LM. These patterns actually occurred in short duration across participants in such a condition, which we have reported as *breakdown – hesitating to identify*, leading to PPWS slightly slower than their normal walking speed (see PPWS in Table 5.5, 1st row).

Compared to the normal walking speed (4.27 km/hr), participants walked slower in both conditions LM (4.00 km/hr) and SS (4.17 km/hr). Using a one-way ANOVA, a significant difference was found among them, $F(2,57) = 3.59$, $p < 0.05$). Planned contrasts revealed that the use of the tactile wearable device decreased walking speed, $t(57) = -2.09$, $p < 0.05$ but that walking with condition LM was equal to walking with condition SS, $t(57) = -1.67$, $p > 0.05$. Post-hoc comparison revealed that the main significant difference was between normal walking and condition LM's pace. Based on these results, we concluded that walking with the wearable tactile technology *for the first time* has disrupted normal walking especially when users have to recall landmark associations.

The development of an internal spatial representation

At the end of each condition, participants were told to recall a recently navigated route and were asked to draw the route including all passed landmarks. Navigated routes were designed to have unusual interconnections and turns such that participants were not able to memorise them easily.

Results showed that participants could recall with reasonable accuracy the shape of both routes with, on average, four of the seven landmarks in both conditions. There was no obvious difference in terms of quality of drawn routes and the number of recalled landmarks across conditions. Mean number of recalled landmarks across conditions was 3.67 (SD 2.25).

Participants' ability to draw maps of the navigated routes may be explained by the MRT theory since they were transforming crossmodal inputs into a reasonably accurate drawing of the navigated area. Specifically, participants visually reported, albeit without thorough details, information that had been given by tactile means.

Based on the quality of drawn routes, we could not conclude that participants were able to fully develop a cognitive map of the navigated environments. This may have been influenced by Bath's complex morphology. It does not contain regular patterns (e.g. grids) and has a number of curved and symmetrical shapes. It may also have been influenced by the fact that TactNav demands low cognitive workload (via mental rotation) which in turn can erode spatial skill (Boari et al., 2012). To understand this complex phenomenon, further study is required.

Navigation errors

Direction

For direction, 25% of the participants made the most mistakes in identifying *half right* and *half left*. An observation revealed that some participants failed to turn correctly due to a slight change in their heading direction after receiving the first directional signal leading to an incorrect move based on the second[90] interpretation.

Tactile interaction is very precise; only a slight difference in current heading angle could lead to error in decision making. Some participants followed the signals so straightforwardly that they did not maintain themselves on the pedestrian footpath. For example, there were two participants that after receiving a *half left* signal at a corner, made that 45-degree left turn and continued with that slightly-left heading, cutting across the street instead of getting onto the footpath on the side of the road. Another example was when a participant received a *straight* signal; they just walked 90-degree straight ahead into the middle of the road instead of making a slight deviation onto the pavement. We believed that participants would be able to develop strategies to conceptualise directional choices given a long-term usage of the system.

We expect that an intensive *in-situ* training and signal timing calibration will easily eliminate choice hesitation and errors.

Landmark

Errors were distributed across landmark categories. Data gathered revealed that there were several patterns of errors. In condition SS, participants were not able to convincingly identify landmarks when several landmarks were cluttered in the same vicinity. In which case, they would call all of those landmarks including irrelevant types. Another error case occurred when participants completely forgot to identify landmarks as they have interpreted the straight signals being given at the location of important landmarks simply as a directional instruction. Participants indicated that as long as the signals guided them onto the right path leading to a destination, they were not worried about not being able to

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[90] Please note that each directional instruction was given as a set of two identical signals with a two-second gap.

identify on-route landmarks. As landmark identification is crucial to navigation completion, we suggest that intensive *in-situ* training will help improve with this situation.

For condition LM, participants had widely reported that they experienced difficulty distinguishing landmarks from direction signals once they started walking. This happened despite the fact that we have compensated the mobility effect by extending signal duration from 1.2 to 2 seconds. Other problems that may be caused by mobility included not being able to recall signal associations and confusing the felt with the other signal. An increase of signal intensity may resolve these practicality matters. In addition, further study could be done on having participants develop their own semantics.

Cognitive workload and navigation confidence

Participants were observed being more conscious when walking condition LM than condition SS. The NASA TLX scores directly reflected this occurrence. For the task load analysis of the two walking conditions (see detailed scores in Appendix 6.2), a paired-samples t-test revealed that the two different types of tactile signals required significant difference levels of task load indexes: mental demand ($t(19) = -4.33$, $p < 0.002$), frustration ($t(19) = -2.91$, $p < 0.05$), effort ($t(19) = -4.68$, $p < 0.002$), and performance ($t(19) = -2.59$, $p < 0.05$). Namely, participants found that condition LM required a higher level of mental demand/effort and were more frustrated than with condition SS. They felt that they performed significantly much better in condition SS than in LM. No significant difference was found on physical and temporal demand (all $p > 0.05$)[91]. Subjectively, participants found it less cognitively demanding to achieve the same level of performance in condition SS than in LM.

We believed that workload scores reversed variation with subjective confidence scores that have been reported earlier, i.e. the less cognitively demanding, the more confidence participants felt towards using the system. Having reported that, both conditions received relatively high confidence scores. Based on our observation, none of the participants showed any sign of frustration or uncertainty with our improved system design walking both conditions.

Interestingly, these task loads index and confidence scores had no direct relationship with their preferences. Participants who preferred the system that provided both directional and landmark information indicated that although it required them to try hard to recognise

[91] For the detailed TLX scores, please see Appendix 6.2.

landmarks in LM condition, they thought that long-term use would be more favorable than the system that only provided directional information especially when they have to navigate unfamiliar areas. A few participants explicitly discussed the relationship of their preferences with the purpose of their journey, stating that the system that provides only directional signals is suitable for questing while the system that provides both directional and landmark information is beneficial for exploration.

Wearability and acceptance

The wearability and aesthetics of the systems are crucial to user acceptance. Clearly our prototype, involving a notebook computer, a controlling board in a backpack and protruding wires, allows for little meaningful evaluation of these issues. We will discuss user acceptance in light of the system's usefulness and users' attitude.

The device acceptability could be partially measured using TAM. According to the usefulness scores, it was clear that all participants looked over the unusual appearance of the prototype, as none of them explicitly stated any concern about its look neither during the course of navigation nor in the questionnaires in which they provided feedback.

In addition to the TAM scores where all participants perceived the system as being very useful and fun for their wayfinding, we asked them to state their attitude towards using the system. In general, participants rated their experience using both systems as very positive (4.25 out of 5 on likert scale, 1 – being very negative and 5 – being very positive).

Based on the two measures, we ideally predict that users are likely to employ the tactile-based system to help them with navigation tasks provided that it is improved in reliability, functionality as well as wearability and aesthetics.

Transformation among frames of references

Compared to visual navigation displays, the nature of guidance information provision in tactile-based systems is fairly different. The system provides egocentric guidance information without forward field of view (FFOV); guidance information includes navigational choices, navigation checking (am I on the right path?) and additional cues such as landmarks and destination without overview information on spatial direction judgments of the objects.

For our tactile navigation system, there exist three frames of references, two fewerfewer than those presented in visual systems[92]. The three frames include a world, an ego and a display frame. Wearing the system on the body completely eliminates the need to map the ego to the display frames because both frames are completely aligned. As a result, the navigation function through the tactile channel involves only two frames, the ego+display and the world. The absence of FFOV and other visual information reduces time delay, disorientation, errors, mental workload and navigation ambiguity that usually occur with visual-based navigation. Evidently, tactile-based displays, our system in particular, require very little transformation and almost no physical or mental rotation.

Tactile display or tactile interaction

Currently TactNav's wayfinding instructions are triggered by whole body movement. In other word, users cannot directly enter any other forms of input which they might wish to, for example, a destination point, a request for rerouting or a request to repeat vibration signals. Lack of obvious means to interact with the system, TactNav could be considered merely as a tactile navigation display. However, if we consider the whole body movement as a macro gesture, one may argue that TactNav may as well be considered as an interactive system. Our future work could explore the interaction side of the system in more detail. Specifically, should the system take any other forms of input rather than just movement, how would it be like?

Limitations with TactNav's evaluation

A major limitation of this evaluation is not having participants using TactNav to navigate unfamiliar areas. Given the look of TactNav (Figure 5.14), participants' safety was our first priority and the walking must not cause any public disturbance[93]. Given its peaceful atmosphere, the city of Bath[94] was chosen as the venue for the experiments.

We were aware that having participants walking in their residential town could possibly bias results on the ability to recall routes. To compensate any potential preconception, we

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[92] Transformation in visual navigation systems occurs among five frames of references: a world, an ego, a head, a display and a control frame (see Chapter 2 for explanation).

[93] To prevent any misunderstanding, we informed the authorities about the experiments.

[94] Bath is a relatively small city with a very low rate of crime and public disorder. The majority of the population are students and the elderly. The general atmosphere is very friendly.

designed unusual and slightly complex yet realistic paths for the experiments. Additionally, routes were unknown to participants.

Figure 5.14 Participants wearing TactNav.

It was proved in both the quantitative and qualitative results described earlier that participants' living duration and their knowledge about the space did not have an influence on their ability to recall navigated routes (as most could not recall routes in detail regardless of their residential duration). Many of the participants had explicitly pinpointed that the routes were complex and that the City of Bath itself contains unstructured (i.e. non-grid) layouts which makes it quite difficult to recall. This led us to believe that somehow our results were not affected by route familiarity.

Nevertheless, we insist that TactNav should be evaluated in unfamiliar areas and in different urban settings to confirm its usability and effectiveness. This is considered as our future research direction.

5.4.6 Conclusion of the field-based evaluation

We had two main objectives in running this experiment, namely, (1) to improve learnability and memorability of landmark signal associations and (2) to investigate the effect of tactile landmark signals on navigation performance in real environments.

Our attempt to improve learnability and memorability has been successful as results demonstrated that the presence of a visual diagram significantly helped improve learnability and a repeating training session ensured memorability. Nevertheless, accuracy performance decreased once we took the system to be evaluated in the field. This may be caused by participants' movement. With respect to a number of possible environmental factors, we had no concrete method to identify them and/or to measure their effect on performance. Further study is required to address this shortcoming. Nonetheless, we hope that the variation of environmental dynamics across conditions and participants would reflect results that might occur in real world use.

We have obtained realistic results and address practicality and user experience[95] issues from users' perspective (Kjeldskov & Graham, 2003). It allowed us not only to test system functionalities but also to explore *in-situ* users' needs and the effects of contextual issues, such as weather conditions and the appearance of actual landmarks, on the usability and effectiveness of the system (Goodman et al., 2004).

On the effect of tactile landmark signals on navigation performance, the results refute all of our hypotheses. The two types of tactile signals used for representing on-route landmarks seem to have the same effect on performance and the ability to recall routes. Specifically, participants performed equally well with both types of signals and could, to some extent, develop an internal spatial representation of navigated environments. First-time users felt more confident with the system that required less cognitive workload and perceived such a system as more useful. However, these index scores had no influence on participants' preferences because participants chose the preferred system on the basis of the navigation purpose for which the system will be used (i.e. questing and exploring). If the sole purpose of having delivered any piece of information is to confirm that the navigator stays on course, a simple notification such as a *straight* signal may be sufficient. On the other hand, if guidance for orientation and a highlighting of interesting spots are needed, the hybrid tactile navigation system is preferable.

Other substantial insights learned from this study are that:

[95] ***Desirable* user experience** aspects can be described as: satisfying, enjoyable, engaging, pleasurable, exciting, entertaining, helpful, motivating, challenging, enhancing sociability, supporting creativity, cognitively stimulating, fun, provocative, surprising, rewarding, and emotionally fulfilling. On the other hand, ***undesirable* user experience** aspects can be described as: boring, frustrating, making one feel guilty, annoying, childish, unpleasant, patronizing, making one feel stupid, cutesy, and gimmicky (Sharp et al., 2011).

- The tactile-based navigation technique offers an alternative low attention interface that can reduce alignment effect[96] by eliminating the needs for mental rotation and the transfer of different frames of references;
- Using tactile navigation displays help reduce variance in navigation and wayfinding performance normally found between men and women in visual navigation.

5.5 Summary

In this chapter, we reported a comparative study of two types of tactile signals used to represent landmarks in the field in order to address RQ4 and RQ5.

We have demonstrated through the design and execution of our field evaluation on *RQ4.2 How do we represent a few types of spatial information?*

For *RQ5.1 Does the system help with different tactile navigation purposes?,* our investigation found evidence to support that the system could be used to help with exploratory navigation.

For the following usability-related *RQ*: *RQ5.2 Can tactile landmark representation "increase/help" with performance/confidence as in visual pedestrian navigation systems?,* the study produced no evidence in substantiation of our hypotheses. Specifically, tactile landmark representation does not increase level of performance and confidence.

In response to *RQ5.3 Is there a problem with the transfer of frames of reference with tactile navigation displays?,* no trace of the issue was found in this or previous field studies reported in Chapter 3.

For the user experience aspects, the work in this chapter addresses *RQ5.4 What are user acceptance and perceived usefulness (practicality) of the tactile navigation system?,* qualitative feedback revealed that users have accepted and perceived the system as useful.

The participation of actual users allowed the studying of complex situated interactions and processes as occurred in navigation tasks (Kjeldskov & Graham, 2003; Goodman et al.,

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[96] Alignment effect refers to the difficulty of using maps that do not align with the body heading direction (Montello, 2005).

2004). Up to this point, we have successfully fulfilled our goals and provided answers to all of the research questions. The next chapter sees a summary of the thesis including outcomes, limitation, contribution as well as suggestions for future work.

If we are facing the right direction, all we have to do is keep on walking.

(Buddhist proverb)

Chapter 6 Conclusion and Future Work

This thesis has proposed new insights around the theoretical and practical issues of tactile pedestrian navigation displays. In this final chapter, Section 6.1 summarises the thesis; Section 6.2 reflects upon RQs' outcomes; Section 6.3 addresses limitations of the research and provides reflection on tactile communication; and finally Section 6.4 concludes the work, provides a brief overview of the research contribution and suggests future research directions.

6.1 Thesis summary

The goal of this thesis is to address the issues surrounding the use of tactile communication in a wearable system for pedestrian navigation tasks in urban spaces. This research was originally motivated by the reported struggles in visual-based navigation displays (e.g. Seager & Stanton Fraser, 2007; Millonig & Schechtner, 2006). It prompted us to identify those problems and then search for an alternative communication channel in order to eventually develop and evaluate a prototyping system that could effectively be used to support wayfinding tasks in ubiquitous environments (Chapter 1).

Chapter 2 established the context for this research by examining existing knowledge in the area of pedestrian navigation in urban environments and the roles of technologies in navigation, as well as cataloging related work in the domain of tactile navigation research. This examination allowed us to elicit requirements for the design and development of tactile navigation displays and provided a set of spatial information types necessary for navigation completion, which included direction, landmark, orientation and confirmation cues. Chapter 2 also elaborated the basis of our research programme, including underlying theories (i.e. MRT, Prenav and Choremes theories), psychophysics of touch, factors affecting tactile perception and characteristics of tactile signals. Finally, it provided a careful examination of the design and usability issues[97] requiring to be investigated.

[97] See the list of RQs in Section 1.2.2.

Chapter 3 addressed an ambiguity surrounding tactile representations of directional information. At the time of this research's commencement (in 2007), two wearable interface layouts, a waist belt and a back array, had each claimed success as directional displays in independent trials, with no published evidence on their comparative performance. Therefore, we replicated their original device and signal designs[98] and directly compared them for a range of tasks, focused exclusively on accuracy and time performance. Both of our comparative experiments were the first of their kind. Chapter 3 reported these two novel direct comparison studies of the two most established wearable device layouts. Results informed HCI practitioners and navigation system designers that the belt afforded better performance than the array for an interpretation of eight directions (according to the Choremes theory that describes primitive turning actions at decision points for urban navigation). The Prenav model can be used to explain these outcomes. According to Prenav, it is not enough to simply provide information via a tactile display; it is critical that such a display is intuitively comprehended (Van Erp, 2007). The performance data and expert evaluations indicated that the belt's placement of actuators was more intuitive and easier to comprehend than that of the array layout.

Based on the waist belt prototype, we then developed a tactile-based navigation system called TactNav. As the original tactile belt studies[99] reported its effectiveness over a visual-based directional display in forested areas, we were interested in investigating both systems' performance in an urban setting. Consequently, we carried out a field evaluation, comparing TactNav with a visual-based navigation system on a mobile device, and reported this work in the second half of Chapter 3. The experiment took place in early 2008 and was the first study[100] that compared the two different sensory-based navigation systems in an urban context. Results from our field evaluation were congruent with those of the original studies in demonstrating advantages of the tactile-based over the visual-based systems. Additionally, directional signals given by TactNav could be used effectively as orientation and confirmation cues. Our results also revealed insights into both systems' practicality in relation to urban environment characteristics (e.g. the effect of city structure and the number of objects within the space on navigation performance).

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[98] For the original belt design, see Van Erp et al., 2005; for the original array design, see Tan et al., 2003.

[99] See Duistermaat (2005), Van Erp & Duistermaat (2005), and Elliott et al. (2006).

[100] See a similar study in Pielot & Boll (2010a).

Previous studies' (Duistermaat, 2005; Van Erp & Duistermaat, 2005; Elliott et al., 2006) and our study's findings could be used to generalise that tactile-based displays provide navigation performance advantages in at least two types of spaces: urban and sparse outdoor environments. Similar to Elliott et al.'s (2010) findings, our findings have confirmed MRT and Prenav theories' predictions that intuitive presentation of directional information via the tactile sense can better support navigation performance and reduce workload. Specifically, TactNav was more robust and effective than the visual-based system because the placement of actuators around the waist allowed an intuitive presentation of eight directions thus allowing automatic behavior in such demanding tasks.

Moving away from experimental-based studies, the first half of Chapter 4 focused on the behavioural aspects of how pedestrians use landmarks, if any, for different navigation purposes. Prior to our attempt to classify important landmarks, existing lists[101] were either location-specific (i.e. very small) and did not represent landmarks in different locations; or very large that some of the landmarks provided were not necessary at the level of pedestrian navigation. Hence, it was crucial that we clarified the number of landmarks that could accommodate the human's limited cognitive ability and the mobile computer system's restricted display capacity, as well as systematically identifying the important ones. In order to inform system designers, in 2009, we employed a survey research method that allowed us to gather a large amount of data at a global scale. Responses from both online and face-to-face respondents produced insights into how people use landmarks in different urban areas for different navigation purposes. It also revealed that landmark usage was influenced by specific landscapes of the cities and navigation purposes. Specifically, pedestrians used landmarks located near decision points when they commuted and quested; they used landmarks located along the routes when they explored. Section 4.3.5 provided the sets of contextually prioritised landmarks upon which our lab-based experiment was built. We proposed that the sets would be useful for any sensory-based navigation applications.

Given the sets of landmarks, it was possible to investigate the practical aspects of tactile landmark representation reported in the second half of Chapter 4. Given non-discrete and

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[101] See the lists of landmarks, published by researchers and used in commercial navigation systems in Appendix A2.1.

highly diverse sets of landmarks, we decided to follow the abstract representation approaches, proposed by Ternes & MacLean (2008) and Loomis & Lederman (1986), as opposed to the symbolic technique. We empirically compared two representation techniques using one and two actuators respectively, with and without the presence of directional signals; both techniques were assessed on their support for learnability, memorability, distinguishability (from directional signals) and accurate performance. To date, the experiment, carried out in 2010, is the only study that has investigated a combination of directional and landmark representation. As the abstract approach required users to memorise vibration patterns and their arbitrary associations, we deployed the Dual Coding theory's mnemonics[102] during signal training sessions. Additionally, the experiment strictly followed Choremes on the number of directions presented. Overall results provided new knowledge that, for landmark representation in a hybrid system, signals should be generated using the dual-actuator technique. The planning, execution and results of this lab-based experiment confirmed the effectiveness of the Choremes and the Dual Coding theories.

Building upon findings established throughout Chapters 3 and 4, TactNav's functionalities were extended to display hybrid spatial information so that it could be evaluated for navigation in the real world. Chapter 5 reported the field based evaluation, carried out in 2011, of the hybrid system. We had two main objectives carrying out such a novel study: (1) to improve signal learnability and (2) to investigate the effect of tactile landmark signals on navigation performance. For the first objective, we attempted to improve landmark signal learnability using the Choremes' improved mnemonics and an additional visual diagram. The attempt was successful as results demonstrated significant progress in signal learnability thus confirmed the Dual Coding's effectiveness.

For the second objective, we carried out TactNav's field evaluation on two conditions, with and without[103] the presence of landmark signals, known as conditions LM and SS respectively. Quantitative results demonstrated that the presence of tactile landmark signals had no effect on navigation performance. While directional signals in both conditions provided wayfinding instructions and orientation cues, both straight (condition SS) and landmark (condition LM) signals acted as additional navigation cues, ensuring that

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[102] Providing a set of images and a label for each vibration stimulus.

[103] In the experimental condition SS, the system generated a straight signal as a confirmation of landmark.

users were on the right route passing important (condition SS) or specific (condition LM) landmarks. However, qualitative data revealed that landmark signals could be useful and were preferable if a highlight of interesting places was required (i.e. for exploratory purpose). The evaluation was done against the usability and user experience goals identified in Chapter 2. This allowed us to identify practical issues regarding the use of TactNav in urban environments including the effect of mobility on signal perception, the reduction of an alignment effect[104], the absence of gender difference on navigation performance, the effect of wearable technology on walking speed, the development of an internal spatial representation, and the increased level of cognitive processing when landmark signals were presented. For this latter phenomenon, the display of landmark signals that required extra effort to memorise them made the system more difficult to understand according to Prenav. However, overall findings, reported in Chapter 5, provided evidence to support our proposal that tactile representation of spatial information could be used effectively to aid navigation and wayfinding in urban environments, thus supporting the Choremes', MRT's and Prenav theories' predictions.

6.2 Thesis outcomes

Regardless of having any assistive tools, navigation tasks require concurrent processes of physical movement and decision making involved in determining the desired direction and target of travel (Bowman, 1998). To support the tasks, navigators usually adopt visual assistive technologies such as paper- or electronic-maps.

However, it has been widely agreed among researchers (e.g. Ishikawa et al., 2008; Liben et al., 2002; Wickens, 1999; Keckmann & Post, 1993; Huang et al., 2012) that using visual tools to aid wayfinding is not easy. It requires multilevel cognitive processing and near perfect synchronisation among at least three frames: the world, the map's orientation, and the navigator's location and viewpoint (Allen, 1999). The more sophisticated the maps, the less effective they are (see various comparative studies in Ishikawa et al., 2008; Coors et al., 2005; Dillemuth, 2005).

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[104] Alignment effect refers to the difficulty of using maps that do not align with the body heading direction (Montello, 2005).

Our research program has focused and investigated on how to better support pedestrian navigation tasks with a new form of tactile interactive systems. In the following subsections, research outcomes are described in terms of RQs that the thesis addresses.

RQ1 What information types should the tactile navigation display provide to pedestrians?

Our first RQ was prompted by an incorrect assumption that pedestrian navigation would be similar to other types of land navigation and would require the same granularity and system functionalities provided by today's visual-based assistive tools. In fact, pedestrian navigation does not follow the concept of distance-based turn-by-turn instructions (currently used in SatNavs mostly for vehicular navigation) because pedestrians do not require the same level of granularity instruction[105] (Burnett, 1998; Pielot & Boll, 2010; Stark et al., 2007). Furthermore, it was reported that navigation with *distance* requires high cognitive effort (Burnett, 1998; May et al., 2003).

Researchers (e.g. Bradley & Dunlop, 2005; May et al., 2003) suggested the lists of at least eight types of spatial information necessary for land navigation (see Section 2.1.3). These lists were reflected in most of the maps and SatNavs; some even contain larger lists. Nevertheless, we have learned through a comprehensive review in Chapter 2 that a human's tactile perception and cognition abilities are limited. As a result, we suggested that the list of spatial information provided in the tactile-based assistive systems should be minimal. We revised the list by carefully analysing tasks[106] required for pedestrian navigation completion and seeking information types that exclusively accommodate those tasks. In summary, the information types that tactile pedestrian navigation systems should provide included *direction*, *landmark*, *orientation*, and *confirmation* cues.

RQ2 How do pedestrians use landmarks for different navigation purposes?

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[105] That is because humans possess inherent skills in that we pass lanes, cut across open spaces when possible and use one-way-streets in both directions (Stark et al., 2007). Furthermore, pedestrians prefer less complex routes to those routes, which are shorter in distance, but contain a greater number of decision points (Weiner et al., 2004).

[106] Including (1) identifying directions to take, (2) identifying/classifying landmarks as points of reference and interest, (3) confirming if they are on the right path, (4) orienting themselves, and (5) controlling their movement towards intended directions and destinations.

RQ2 was prompted by lack of clarification of the comparative importance of different landmarks and their usage for three navigation purposes[107] in urban settings. Our empirical study reported in Chapter 4 contributed small yet significant new facts to the body of knowledge on this matter. Results from both on-line questionnaires and face-to-face interviews allowed us to identify that landmarks have been used differently mostly depending on navigation purposes and on their locations in relation to the navigated paths. Outcomes for RQ2 have been broken down and described in the following three sub-RQs.

RQ2.1 Do pedestrians use landmarks differently for the three different navigation purposes of commuting, questing and exploring?

Existing knowledge informed us that landmarks used during the course of navigation are located both on-route and off-route (e.g. distant landmarks). On-route landmarks are always being used as references for orientation and confirmation, and occasionally being used to disambiguate turning instructions. Off-route landmarks that are not contiguous to the navigated path such as mountain or river are reported to have some orientation value (Lovelace et al., 1999).

Results from our survey study revealed that pedestrians would use different sets of landmarks with different frequency of use for different navigation purposes. A substantial finding explained the paradox of landmark's roles in wayfinding. For example, navigating in the same area, a person may find commonly important landmarks such as religious places as having no value for their commuting but may find it crucial to navigation completion for a questing purpose. Additionally, a number of landmarks used were significantly more in unfamiliar areas than familiar areas.

RQ2.2 When do pedestrians use landmarks during navigation?

Reponses from our participants revealed that they need to depend on landmarks most when they quest or explore the area. The usage timing of the two purposes was reported to be different. During the quest journey, landmarks located near decision points were memorised prior to the commencement of the journey and later recalled to clarify the change of direction just "before" the navigator making decision at each manoeuvre.

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[107] The three navigation purposes are commuting, questing and exploring.

On the other hand, during the exploration journey, two usage patterns were found. Landmarks distributed along the path were constantly being used to confirm that the navigator was on-route and they were used frequently on long segments of the route (cf. Allen, 1997). Landmarks situated near decision points were being used to confirm their choice of turns "after" the navigator making decision.

RQ2.3 What are the most important landmarks for each navigation purpose?

Synthesising data gathered from both questionnaires and face-to-face interviews, we were able to provide the lists of important landmarks for each navigation purpose (Table 4.2).

RQ3 What is the effective form of tactile displays for pedestrian navigation? and RQ4 How can we represent spatial information via the chosen device? Specifically, which representation technique should be used for each type of spatial information?

Various forms of tactile directional displays have been proposed; each of them was designed to be worn on different body sites such as head, torso and thighs (see Table 2.2). In Chapter 3, we argued that the best location for the display of spatial information is the torso area, leading to the focus on only two popular device layouts: the back array and the waist belt. We then built the two prototypes following their original designs.

Results from two lab-based experiments and a field-based evaluation allowed us to establish that, for RQ3, the *waist belt* embedded by eight actuators is an effective form of a wearable device, and for RQ4, an absolute-point vibration technique should be used to display egocentric directions, confirmation and orientation cues.

Following the research on landmark usage reported in Chapter 4 Section 4.3, we have investigated an appropriate representation technique for landmarks that works effectively with direction representation on a waist belt device. Our attempt to present hybrid spatial information was the first of its kind. Chapter 4 Section 4.4 reported results suggesting that, for RQ4, the dual-actuator approach for tactile landmark representation worked effectively with the absolute vibration technique for tactile direction representation.

RQ5 What is the tactile navigation system's performance?

RQ5 was framed by the lack of knowledge on usability and user experience as well as practicality issues surrounding the use of the tactile navigation displays in the field. Outcomes for RQ5 have been broken down and described in the following four sub-RQs.

RQ5.1 Does the system help with different navigation purposes?

The field evaluation reported in Chapters 3 and 5 confirmed that the system could be used effectively for quest and exploration.

RQ5.2 Can tactile landmark representation "increase/help" with performance/confidence as in visual pedestrian navigation systems?

Based on results reported in Chapter 5, we had no substantial evidence to believe that the presence of tactile landmark signals helps increase level of performance and confidence. We have learned that mobility had an effect on tactile perception of landmark signals which in turn impeded users' performance and confidence. Nevertheless, we had no supporting proof as to how and how much, if any, the changing environments impact these outcomes. Further studies are required to understand these complex phenomena and their causes.

RQ5.3 Is there a problem with the transfer of frames of reference with tactile navigation displays?

Evidently, the interaction techniques deployed in TactNav impose very little or no demand for the transfer of frames of reference because they naturally eliminated the needs for mental and physical rotation (normally used to align different frames in visual-based navigation).

RQ5.4 What are user acceptance and perceived usefulness (practicality) of the tactile navigation system?

For the final RQ, we were interested in the likelihood of technology adoption. We theorised that TAM could be used as a fundamental determinant to predict and explain the use of our proposed technology. Despite the prototype's unattractive look, all participants stated a very positive attitude towards the system because of their perceived usefulness and ease of use. Provided an improvement in system aesthetics, participants are most likely to adopt the hybrid system especially when navigating unfamiliar areas.

However, in reality, we are aware that users' individual difference could influence acceptance of new technology. These differences include cognitive style, personality (e.g. degree of defensiveness, risk-taking propensity), demographics (e.g. age and education), and user-situational variables (e.g. training, experience, and user involvement) (see Alavi

& Joachimsthaler, 1992). Therefore, further research on user acceptance and system practicality are required for the prediction of wearable technology adoption.

6.3 Discussion and reflection

After addressing all of our original research questions, we are now in a position to discuss and reflect on how well we have answered them. This section starts in subsection 6.3.1 with a note on the limitations of positioning technology at the time the field studies were carried out. Then we provide a summary of the drawbacks with research methods and experimental designs in subsection 6.3.2. Subsection 6.3.3 reflects on the roles of spatial information and subsection 6.3.4 summarises the advantages and disadvantages of tactile communication and tactile-based navigation systems.

6.3.1 Location technology used in this research

With current advances in GPS technology (as of 2012), data broadcast from a constellation of satellites around the Earth provides highly synchronised clocks with trilateration[108] giving 5-20 meters accuracy. At the time of the research[109], positioning coverage in urban canyons was not 100% accurate and it could become much worse if the environment contained high structures or buildings (Raper et al., 2007; RIN, 2011). We had no choice but to assume that the city of Bath, a location where the field experiments took place, had an acceptable level of positioning accuracy given that the cityscape[110] allowed satellite signal availability.

Our two field evaluations, carried out in 2008 and 2011 respectively, relied on this technology to provide navigation guidance. We observed that there were much higher occurrences of GPS signal disappearance in the first than in the second studies, leading to user's higher level of frustration and poorer time performance. It seems, therefore, that the GPS coverage has improved over time. Ultimately, we believe that the future of GPS

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[108] Trilateration is a method for determining the intersections of three sphere surfaces given the centres and radii of the three spheres.

[109] The research program took place during 2007 - 2011.

[110] The experimental routes, contains only low-rise buildings.

looks bright because in the next decade three worldwide navigation satellite systems[111] are due to join GPS. Collectively, they will be called Global Navigation Satellite Systems (GNSS); they are expected to give better coverage, especially in urban canyons (RIN, 2011). Improving the accuracy of positioning technology is however beyond the scope of this thesis.

6.3.2 Drawbacks with research methods and experimental designs

Earlier, we have discussed the limitations of each study in the corresponding chapter. In this subsection, we reexamine the limitations across chapters.

Some may argue that with navigation tasks, field study is the most suitable method for evaluation. We decided to adopt a mixed-methods approach of survey research, lab-based studies and field trials throughout the research programme because each was considered suitable for the purpose of a given empirical study.

Lab studies

To evaluate the choices of device layouts (reported in Chapter 3) and signal designs (reported in Chapter 4), we chose lab-based experiments. Although not entirely realistic, lab-based studies allowed us to manipulate experimental variables and collect quantitative measurements such as errors and performance time for subsequent data analysis without interference from external factors.

We were aware that some of our lab studies' experimental design choices could be considered as drawbacks. One may argue that not having our participants wearing a noise cancellation device in all three lab studies (reported in Chapters 3 and 4) could impact signal recognition performance. We decided to leave participants' auditory channel receptive to any sound produced by the vibration because stimuli perceived by both sensory channels were coherent thereby yielding a positive effect, i.e. sensory augmentation (Turchet, 2010; Gallace & Spence, 2008; Klatzky & Lederman, 2005). Furthermore, we kept other sounds in the controlled environment to a minimum.

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[111] The three systems include Russia's GLONASS (~2012), Europe's Galileo (~2018) and China's Compass (~2020).

We deliberately provided no training on direction signals to participants in the two lab studies, reported in Chapter 3, because we aimed to test the two devices' intuitiveness according to the MRT and the Prenav theories.

The major issue with the lab experiments reported in Chapter 3 may be not isolating the three factors (i.e. stimuli patterns, body contact areas and actuator layouts[112]) which may contribute to the belt's achieving better performance. As we aimed to directly compare each device layout and signal generation on their effectiveness, we had to fully replicate the original designs. Future research could investigate the effects of alternative instantiations in each of these dimensions.

Survey study

To gather information on how people use landmarks during the course of navigation, we chose to conduct a survey (reported in Chapter 4). The method is considered contextually insensitive and it allows no variable manipulation (Kjeldskov & Graham, 2003). As a result, collected data could be incomplete or unreliable because respondents were independent of their navigated environments. Nonetheless, the method allowed us to collect descriptive data from large samples at low cost within a short period of time, supporting broad generalisation of results (Kjeldskov & Graham, 2003).

For the study design, online questionnaires were sent out only to highly educated respondents who live in modernised societies where there is high penetration of computing resources and technological advancements. This could lead to sampling issues such as sample and self-selection biases (see Wright, 2005). Furthermore, aside from some basic demographic data, we could not guarantee respondents' real characteristics and their level of navigation skills because all information was self-reported.

In order to increase credibility of the survey results, multiple online surveys with the same or different types of respondents should be conducted (Wright, 2005) so that we could gain reliable outcomes on how people generally use landmarks to aid their navigation in urban areas.

Field studies

To evaluate the system's design and to investigate practical issues, we carried out field studies, reported in Chapters 3 and 5. This research method allowed us to gain realistic

[112] Saltatory cues on a back array ***vs*** absolute cues on a waist belt

results and insights into complex situated interactions. However, it was quite difficult to collect data and we had limited control of the experiment and the environments (Kjeldskov & Graham, 2003).

The field study's disadvantages were realised in the experiment reported in Chapter 3. There were situations when the weather conditions made it slightly more difficult to walk with participants' normal effort. We did not abort the experiment because we hoped that it increased the realism of using both types of navigation systems in the real world. It is worth noting that lessons learnt from this study helped us better design the second field evaluation, reported in Chapter 5.

A limitation of this thesis was not having the system evaluated in different spaces. We have discussed and elaborated this point quite thoroughly in Section 5.4.5, suggesting the system evaluations in areas unfamiliar to the participants. It is critical that this should be done only if the prototype's appearance (Figure 5.14) is improved for fear that it could compromise participants' safety given global concerns about terrorism.

6.3.3 Reflection on roles of spatial information

In Chapter 2, reviewing related research suggested that our tactile-based navigation system should provide four types of information: direction, landmark, orientation cues and confirmation cues. We would like to clarify this point in relation to the roles of spatial information in different sensory-based systems.

There are two important types of spatial information, direction and landmark (Bradley & Dunlop, 2005). We found that their roles in navigation completion are different in visual-based and tactile-based systems.

With visual-based navigation, pedestrians use visual directional information as wayfinding instructions. They use landmarks as confirmation and orientation cues because visual navigation naturally requires mental orientation and transformation among frames of reference (see Section 1.1.2 and Appendix A2.5). Landmarks are reported to help increase navigation confidence and reduce navigation errors (May & Ross, 2005).

On the other hand, with tactile-based navigation, directional signals can be used as wayfinding instructions as well as orientation and confirmation cues. According to our studies' results, they help increase navigation confidence. With the absence of the intermediate frame of reference (i.e. the display frame), navigating with a tactile-based system required no mental orientation and transformation. As a result, pedestrians no longer need to rely on landmark signals for confirmation and orientation. Albeit not necessary, landmark signals can be used as confirmation cues. Consequently, their role can be reduced to merely a notification of on-route or destination landmarks, if required.

6.3.4 Reflection on advantages and limitations of tactile communication and tactile-based navigation systems

Advantages of tactile communication and tactile-based navigation systems

Touch can be used not only to draw attention but also to profoundly express the meaning of interactions (Tan & Pentland, 2005). This is because, in reality, we touch intending to perform tasks, communicate messages and connect emotionally and physically to living things (Brian et al., 2004). The touch sensory channel is different from the visual and audio channels as it is bi-directional, i.e. it can be used as both input and output to the systems. A major benefit of communication via touch is the large number of skin receptors because skin is the largest sensory organ.

Gregory (1967) suggested that touch constitutes a more primitive sensory modality compared to visual and auditory in that it requires minimal cognitive effort and provides information of immediate value. To explain this further, if we observe how the human brain processes visual and audio information, we need to transform what we see and hear into hypotheses and try to make sense of these external/distant stimuli. In contrast with touch, it occurs when our body is in direct contact with stimuli and the environment. However, we are much more accustomed to gathering information through the visual modality than via the tactile modality (Gallace & Spence, 2008).

Touch could be used as a fundamental unisensory mode for communication because tactile consciousness is well-differentiated from the consciousness of stimuli presented in other sensory modalities (Gallace & Spence, 2008; Van Erp, 2003; Wickens, 1980). In other words, the perception of tactile information is less likely to be affected by perception via other modalities unless there is an attempt to facilitate or impair tactile awareness (Gallace & Spence, 2008).

The use of touch interaction in human computer interaction is still at an early stage. Researchers (Subramanian et al., 2005; Nesbitt, 2005; Tan et al., 2003) have suggested that touch feedback could be used as an alternative to the visual and auditory channels. It helps reduce clutter in either space, allowing for an increased number of simultaneous distinguishable signals to be perceived by the user. As a result, this touch feedback could be invaluable when users' attention has to be split into several loci. MacLean (2008a) noted that touch is a lightweight communication that is suitable for interaction on the move where events and state detection of the environment should be done subconsciously. Previous research (e.g. Castle & Dobbins, 2006; Van Erp & Duistermaat, 2005; Elliott et al., 2006; Pielot & Boll, 2010a) as well as results from all of our empirical studies suggests that tactile information is most efficient for navigation tasks. On this final point, the advantages of tactile navigation systems can be summarised as follows.

Performance over visual navigation systems

Existing visual-based navigation systems impose extensive cognitive demands for transformations and mental rotations (Wickens, 1999). Demonstrated throughout the thesis, the tactile navigation system imposed low mental workload, allowing users to perform their tasks with low stress level and error rates. The system provided useful information in a timely manner and allowed the navigators to achieve their navigation goals while simultaneously engaging with other tasks or objects in the environment.

Performance for gender and individual differences

Although we did not seek to directly tease out the effect on system performance of individual differences in age, gender, navigation experience and spatial ability, results gathered throughout the thesis suggested that people of different levels of skills, gender and background are likely to perform equally well using TactNav.

Intuitive interaction

It requires a number of skills to comprehend map reading (Allen, 1999) and a high level of cognitive effort to use visual-based navigation systems (Duistermaat, 2005; Raisamo & Myllymaa, 2010; Elliott et al., 2010).

On the contrary, empirical studies presented in this thesis illustrated that it required very little training to learn arbitrary tactile landmark signals. Importantly, it required no effort to learn tactile directional concepts using an absolute-point vibration technique. Unlike with their visual counterparts, information processing efficiency, cognitive ability, working memory capability and prior knowledge are not determinants of the comprehension of tactile directional instructions. Overall, interaction with tactile-based systems has been shown to be intuitive, not cognitively cumbersome or obtrusive.

Limitations of tactile communication and tactile-based navigation systems

Despite the fact that the touch sense is rich compared to the other senses, there are physical limitations. First, spatial resolution on each part of the body is fairly limited; hence, it cannot represent very complex graphical patterns (Kaczmarek & Bach-y-Rita, 1995). Secondly, it lacks the ability to provide overview information (Jansson, 2005) and is restricted in carrying semantically rich information (Subramanian et al., 2005). Additionally, too much skin stimulation leads to fatigue (Schiffman, 1976). Finally, the fact that touch has so many attributes that we can manipulate makes it both potentially powerful and quite complicated to design for (Fisher et al., 2004).

In terms of a personal–public spectrum, touch communication is very personal. It is interaction design and experience design for an individual. This experience cannot be shared unless the design is intended for a group. Touch is most easily deployed in a system for one user (and is even more limited than the small visual-based display of a mobile phone screen).

Other problems include actuator performance, mechanical transmission difficulties, safety, absence of software modelling, and understanding of psychophysical aspects of the system (Fisher et al., 2004).

Although this thesis has demonstrated that tactile-based navigation systems are promising, many problems still confront the development of effective and practical ones. For instance, we have highlighted in Chapter 5 that mobility has a significant impact on tactile perception. Although increasing signal strength could resolve the issue, we have yet to investigate whether signal strength above the recommended frequency (i.e. 200 Hz) would be disturbing or quickly lead to fatigue and skin adaptation. We conclude this subsection by noting the major disadvantages of tactile navigation systems based on our empirical studies.

Lack of an overview function

The major flaw of the tactile navigation display lies in the fact that it cannot provide an overview of the routes, which in turn reduces the user’s confidence during the course of navigation. In which case, should any application require an overview of the route or setting, multimodality should be considered.

Limited bandwidth

We have learned that tactile information cannot be used to communicate large numbers of symbols or provide for many fast changes because the bandwidth of the channel is low

(Subramanian et al., 2005) and human cognitive capacity is limited (Schiffman, 1976). In our case, the trade-off for wearability has made the matter worse because our tactile display allowed small contact areas, i.e. points around the waist. As a result, the information obtained through the display was very restricted. Furthermore, we learned from results reported in Chapter 5 that this limited bandwidth suffers from a mobility effect (i.e. vibration perception on the torso area decreased when moving).

To address these problems, a large amount of research still needs to be done on the expansion of tactile bandwidth, learnability and memorability improvement as well as the minimisation or management of movement effects.

6.4 Conclusion and future work

6.4.1 Conclusion

The thesis has made a significant contribution to the field of tactile interaction design for pedestrian navigation. Our thesis findings have contributed to an understanding of the design, development, usability and user experience issues of tactile navigation displays. Prior to our research, much of the work in the field emphasised providing only one type of spatial information: direction. We were compelled to investigate how the research domain could be extended. This research is the first that has taken a step forward into demonstrating that displaying tactile landmark signals is possible and effective, given carefully designed signal representation techniques for different information types.

It is worth noting that we do not seek to claim that tactile displays are in general superior to visual displays, as each has their particular advantages. Implications from our studies could be summarised that tactile displays provide effective local guidance while visual displays offer better overviews of the areas and routes. Nonetheless, we are aware that regardless of tactile displays' performance advantages for waypoint navigation, visual displays, either in the forms of a SatNav or an application embedded in smart phones, remain the dominant choice for most mobile users.

In our work, we have sought to tackle major challenges in developing practical wearable tactile-based navigation systems that can transmit useful spatial information to pedestrians. The attempt was warranted since it provided practitioners and designers with novel understandings and insights regarding the design and development of systems that can effectively support navigation in urban environments. The thesis can be used as a basis or suggestions of directions for future research that is relevant to the design of tactile-based navigation systems for different types of users performing different tasks in different types of space. For instance, the next generation of tactile systems could effectively allow a visually disabled user navigating unfamiliar areas, a hiker traversing elevated terrains, a soldier finding targets in outdoor environments, a firefighter navigating a smoke-filled building, or a rescuer searching for survivors in demanding conditions.

Having completed our research programme, we realise that the challenges facing tactile interaction design are still great. Nevertheless, we strongly believe that the HCI community and system designers will benefit in numerous ways from tactile capability. The progress within the area still requires understanding of a wide range of aspects including for example interface and interaction design, human cognitive ability, and information representation, alongside technological advancements in GPS coverage and hardware components.

To conclude this thesis, we review its research contributions to the domain of tactile displays for pedestrian navigation.

Research contributions

Each chapter of the thesis has its own conclusion section and the previous sections in this chapter have summarised the chapters and discussed the outcomes and limitations. Hence, those detailed conclusions will not be repeated here. Instead, this section will outline the overall substantial contributions, both theoretical and practical, of this thesis to the body of knowledge.

Addressing the first two RQs, we made a theoretical contribution by developing the list of necessary spatial information types for tactile-based systems and the lists of landmarks used for different navigation purposes (described in Chapters 2 and 4 accordingly). They could be used to inform HCI practitioners, serving as a basis for the design of tactile navigation displays that we have illustrated throughout our practical studies. Additionally, results from all of our empirical studies reported throughout the thesis confirmed the underlying theories including the Choremes, Dual Coding, Prenav and MRT theories.

Addressing RQs 3-5, we made a practical contribution. The contribution came in the form of requirements and suggestions for the development of the system prototypes. The application of these requirements has been demonstrated throughout the development and evaluations of TactNav reported in Chapters 3, 4 and 5. The contribution also included heuristics for tactile representation techniques, arbitrary signal training requirements and improvements, the system's wearability as well as an initial understanding of the impact that mobility and the real context of use have on navigation performance.

6.4.2 Future work

The use of tactile displays has yet to become common practice compared to the use of other traditional senses for communicating information in HCI. Evidence gathered throughout our research programme has shown that our system could be used effectively to aid navigation in normal as well as reduced visibility and audibility environments and in attention demanding and high visual workload environments. Nevertheless, the findings led to new questions and requirements for system improvement. These emergent issues are considered as our future research directions.

Learnability and memorability improvement

It was demonstrated in Chapters 4 and 5 that following the Dual Coding theory[113] (Paivio, 1986), learnability and memorability could be improved. However, it was apparent that the tactile channel's bandwidth is fairly limited. Although our underlying system has a relatively simple structure, its complexity came from a combination of representing various types of tactile spatial information and a number of learned arbitrary associations.

To learn landmarks, our participants could cope with seven arbitrary associations in the lab environment but six in the field. In reality, there are many more landmark categories to be represented. Therefore, it would be beneficial if the threshold of bandwidth can be expanded, not only to cope with more landmarks but also to make the already-learned signals resilient to mobility and environmental noise effects. This may be achieved by having users develop their own semantics (Cohen, 1993; Cohen, 1994a, Cohen, 1994b; Edworthy & Hards, 1999; Bonebright & Nees, 2007), that is, allowing users themselves to define the associations between vibrotactile signals and landmarks.

User groups

The system proposed here could potentially be extended and used for wider user groups such as pedestrians with severe visual impairment or elderly people. One of the challenges in tactile research includes understanding the effect of aging on tactile perception both physically and cognitively. With an elderly population, they could suffer deterioration in

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[113] Training with mnemonics, i.e. providing both a label and images

various areas such as loss of hearing, loss of visual ability, physical and cognitive functions, peripheral sensation and skin detection ability (Goodman et al., 2004). Visually-impaired users are often very sensitive to tactile stimuli and require a different set of spatial information for navigation (see Table 2.1).

Therefore, further system design and evaluation for each specific user group will be required because they possess different characteristics and skills, and may have different opinions on usability and acceptability.

Aesthetics

We have acknowledged that the current prototype's physical design was not the best possible realisation of the tactile interface. With a greater budget and advanced technology, the device itself could be made smaller with fewer wires or equipped with wireless technology.

Error reduction and additional system functionalities

Error reduction

Based on the results of the experiment reported in Chapter 5, there are three main types of navigation errors: (1) participants made an incorrect turn, (2) participants were unable to identify landmarks, and (3) participants incorrectly identified landmarks. Qualitative feedback and observation revealed that the first type of errors happened when there was an unexpected change of participants' heading angle during which tactile signals were generated. We expect that extensive and in-situ training should help prevent this type of error.

Both types of errors in landmark identification happened when participants were either unable to recall landmark associations, or unable to distinguish direction from landmark signals. The roots of these errors were unclear. They could be caused by mobility effect, tactile clutter[114], spatial and temporal masking or all of them combined. A revision of signal design may be required to prevent tactile clutter and spatial and temporal masking. Increasing signal strength may help reduce the movement effect. Within these general concerns, there are vast numbers of specific issues requiring investigation, such as how

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[114] Multiple tactile messages being presented both sequentially and simultaneously (for landmarks) may lead to reduced detection and comprehension or a sensory overload situation.

strong the signals should be. Therefore, many studies still need to be carried out to identify the actual causes of these errors in order to resolve them effectively.

Additional system functionalities

During the TactNav evaluation, we gathered recommendations for improvement of the system's functions. These functions include providing:

- An initialisation interface which allows users to input destinations
- A recovery signal or a re-route function in case of error
- A confirmation signal after the correct turn has been made
- A manual control of signal generation

We foresee that further development of these ideas would be beneficial.

Long-term use

Due to resource limitations, our research has been restricted to a system's evaluation over a short period. Future studies need to address benefits and issues that are related to a long period of use such as heat accumulation from vibration or fatigue from wearing the system.

Tactile navigation model

In Chapter 5, we derived a preliminary version of a tactile navigation process (Figure 5.13), portraying the interactive aspects of pedestrians using our tactile navigation system in specific urban contexts. Research in tactile navigation is still in its early stage and the work presented here provides a first step in understanding how we interact, decide and act when deploying a hybrid touch-based system for navigation tasks. This process model needs to be verified with wider user groups, in various urban settings and situations, thereby allowing us to better support pedestrian navigation tasks by tactile-based displays.

Glossary

Amplitude: is a magnitude of the wave (how high it goes on the *y* axis). For example, in Figure 2.12, the bottom wave has a higher amplitude than the top wave.

Articulatory suppression: refers to the mask of tactile stimulus by verbal suppression. Miles & Borthwick (1996) had participants saying the word "the" continuously and counting from 1-3 backwards soon after their body parts had experienced the touch in order to see the effect of verbal suppression.

Attention: refers to the focus of mental resources on information/cognition process salient at a given time. It comes from sensation + memory + thought process. Attention could be controlled or automatic. After being processed, it leads to actions.

Chronometer: is an instrument for measuring time, especially one designed to keep accurate time in spite of motion or variations in temperature, humidity, and air pressure. It is used in conjunction with astronomical observation to determine longitude (Darling, 2011).

Cognition: is what goes on in our heads when we carry out our everyday activities (Sharp et al., 2007). Cognition typically involves a range of processes including: attention, perception & recognition, remembering, producing & learning language (i.e. reading, writing, speaking and listening) as well as problem solving, planning, reasoning and decision making (Sharp et al., 2007).

Crossmodal masking: refers to the mask of a stimulus in one modality by a stimulus generated using another modality (see Gescheider & Niblette, 1967).

Dead reckoning: is a way of calculating the position of a ship or aircraft using only information about the direction and distance it has travelled from a known point (Beauregard, 2007). These data were used to estimate a ship's position and heading (Spera & Strom, 2002). The technique is known today for being extremely inaccurate.

Detection: refers to the ability to sense that they are being stimulated by some form of energy (Kostopoulos et al., 2007).

Discrimination: means being able to perceive one pattern of stimulation as different from another (Kostopoulos et al., 2007).

Distance: is a numerical description of how far apart objects are (Keay, 1989).

Earcons: are abstract, structured synthetic tones that can be used to represent parts of an interface. The sound design manipulates timbre, pitch, register, rhythm, intensity and a combination of these attributes. See Brewster et al., 1999; 2002; 2003.

Grid reference: is a method of locating a point on a map by a number referring to the lines of a grid drawn upon the map and to subdivisions of the space between the lines (Keay, 1989).

Hapticons or Haptic icons: are brief computer-generated signals, displayed to a user through force or tactile feedback to convey information such as event notification, identity, content or state (MacLean & Enriquez, 2003). Hapticons' pattern design follows Multidemensional Scaling Analysis (MDS)[115], achieved by manipulation of signals' frequency, amplitude, waveform and duration (for the design and evaluation of Hapticons see in MacLean & Enriquez (2003), Chan et al. (2005), and Ternes & MacLean (2008)).

Locale navigation: An individual forms a mental representation of the surroundings and is able to plan routes between any locations within the area. This is in fact comparable to the construction of a cognitive map. This strategy is used to plan a path from one to another destination within the area (Redish, 1999).

Map: is a diagrammatic two-dimensional representation of an area of land or sea showing the spatial arrangement or distribution of physical features over an area (O'Connor & Robertson, 2002).

Marginal information: refers to all explanatory information given in the margin of a map which clarifies, defines, illustrates, and/or supplements the graphic portion of the sheet (Keay, 1989).

Modality fission: refers to the process of splitting semantic meaning from a modality-free into different modality streams for presenting back to users via appropriate output channels.

Modality fusion: refers to the process of combining multiple modality input streams into a single result which is modality-free but rich in semantic.

[115] A technique focusing on differentiality of signals (for more details, see Cox (1988)).

Nautical chart: is a graphical representation of a maritime area and adjacent coastal regions (Calder, 2002).

Navigational choice: is a choice to turn in some direction from the current heading.

Navigation strategies: Humans and animals use several strategies to navigate visually (Redish, 1999). These strategies include random, taxon, praxic, route and locale navigation.

Pedestrian: is a person walking along a road or in a developed area.

Pedestrian navigation: is a form of land navigation, in particular, navigation on foot.

Percentage preferred walking speed (PPWS): refers to the extent to which the use of the wearable device disrupts normal walking. PPWS is calculated by dividing distance travelled by time. It is then compared with normal walking speed. The higher the difference between the PPWS and the normal walking speed, the higher the effect of the device (Petrie et al., 1998).

Perception: is a human cognitive process by which we recognise, organise, and make sense of stimuli in our environment.

Praxic navigation: An individual follows a fixed motor program. For example, a person navigates by always starting from the same point of origin in the same orientation to a fixed location. In this strategy, an individual may have remembered to turn left at point A and then turn right at point B. This strategy is found to be used in the commute mode of navigation (Redish, 1999).

Quadrant: is an instrument used in astronomy and navigation for taking an angular measurement of the altitude of stars, typically consisting of a graduated arc of 90° and a sighting mechanism attached to a movable arm (Darling, 2011).

Random navigation: An individual has no information about the location of the platform and is forced to search randomly. This is comparable to exploratory navigation purpose described in the previous subsection. A traveller might spend a significant amount of time exploring the environment. The drawback of this strategy is that it is highly likely that a person can get lost (Redish, 1999).

Recall: is the process whereby individuals actively search their memories to retrieve a particular piece of past event or information.

Recognition: is the process of identification of something already known; it involves searching our memory and then deciding whether the piece of information matches what we have in memory stores (Sharp et al., 2007). It also refers to the ability to identify stimuli as well as to detect a particular pattern of stimulation (Kostopoulos et al., 2007).

Route navigation: An individual associates directions with visual cues, e.g. turn left at the church. The strategy can possibly entail a sequence of subgoals. Route navigation can be considered as a combination of taxon and praxic sequences (Redish, 1999).

Scale: The scale of a map is defined as the ratio of a distance on the map to the corresponding distance on the ground (Keay, 1989).

Sextant: is an instrument with a graduated arc of 60 degrees and a sighting mechanism, used for measuring the angular distances between objects and for taking altitudes in navigation (Darling, 2011).

Sign: is an entity that signifies another entity (Keay, 1989). Signs on maps are notices to instruct, advise, inform, or warn map users. For example, a compass sign on a map indicates map orientation.

Subitising: refers to the rapid, accurate, and confident judgments of number performed for small numbers of items (Kaufman et al., 1949) while counting is the action of finding the number of elements of a finite set of objects.

Survey knowledge: represents knowledge about interconnections between discrete features of locations and routes of the area known by the individual (Goldin & Thorndyke, 1983).

Tactons: are a set of abstract interface widgets; are similar to Braille in the same way that visual icons are similar to text, or Earcons are similar to synthetic speech. The design of Tactons relied on the encoding strategy using parameters of cutaneous perception where each of the tactile parameters (i.e. waveform, frequency, amplitude, and duration) is varied to encode information. For the design and evaluation of Tactons, see Brewster & Brown (2004), Brown & Kaaresoja (2006), Brown et al. (2005, 2006a, 2006b), and Hoggan & Brewster (2006a, 2006b, 2007).

Taxon navigation: An individual moves toward visible cues (i.e. landmarks), which leads to the arrival point. It is also known as orienting or beaconing strategy (Redish, 1999).

User acceptance: is defined as the demonstrable willingness within a user group to employ information technology for the tasks it is designed to support (Dillon & Morris, 1996).

Voluntary body movement (efferent command): refers to the ability to control movement of muscles used in touching (Loomis & Lederman, 1986).

Appendix 1 Additional Information for Field Evaluation

A1.1 Experimental route

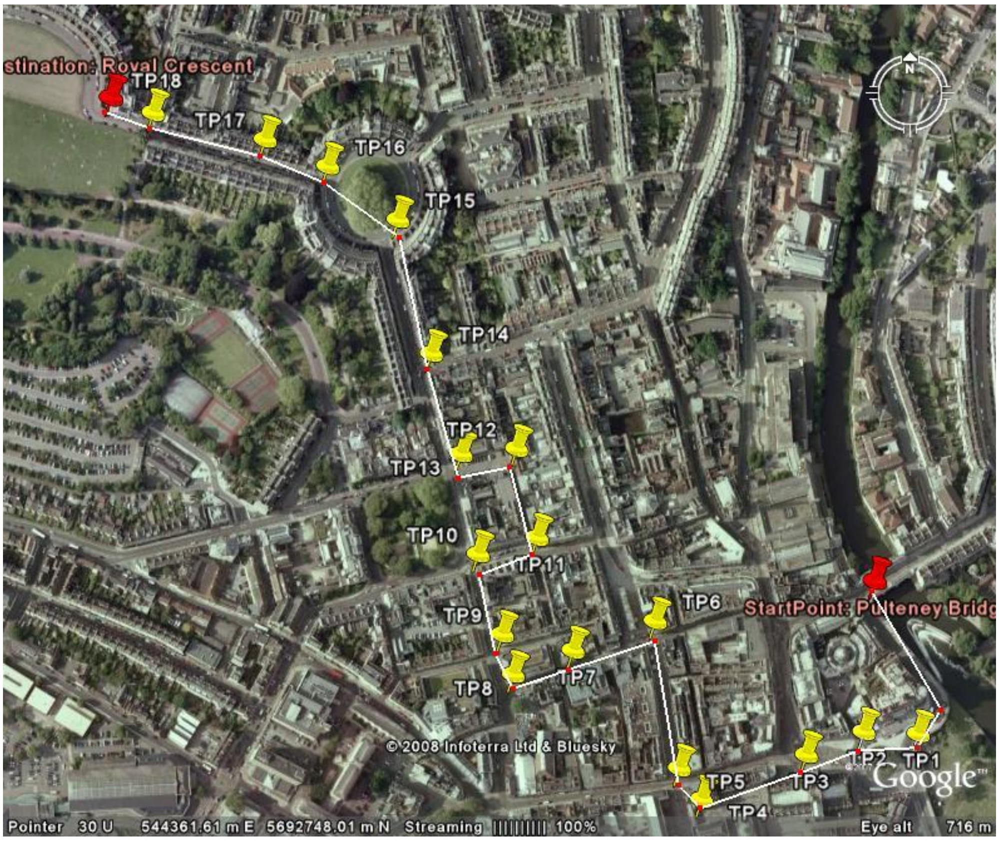


Figure A1.1 Experimental route

A1.2 Summary of turning points

Table A1.1 A summary of turning points by direction.

Direction	Number of Turns
Left	5
Half left	1
Straight	7
Half right	1
Right	4

Appendix 2 Landmarks

A2.1 Landmarks in literature and those currently used in assistive navigation systems

Table A2.1 summarises the nature and the key features of previous landmark research. Many early landmark studies were limited to the vehicular navigation domain; all of the proposed lists of useful landmarks for pedestrians were limited to specific locations or navigation purposes.

Table A2.1 Summary of the list of useful landmark studies (partially taken from Burnett, 1998)

Authors	**Studied location**	**Nature of study**	**List of landmarks**
Davis & Schmandt (1989)	Boston, USA	Evaluation of speech-only route guidance system (vehicular navigation)	Traffic lights, stop signs, bridges, petrol stations
Alm (1990)	Linköping, Sweden	Route descriptions given by locals (vehicular navigation)	Traffic lights, traffic and place name signs, shops, petrol station, bridges
Akamatsu et al. (1994)	Tokyo, Japan	Verbal protocols given when using navigation systems (vehicular navigation)	Building, street name signs, crossroad signs, place name signs, traffic signs
Green et al. (1995)	Michigan, USA	Evaluations of a simulated route guidance system (vehicular navigation)	Traffic lights, stop signs, bridges
Burnett (1998)	Derby, UK	Driver’s information requirements for route guidance systems (vehicular navigation)	Traffic lights, pelican crossing, bridge over road, hump-backed bridge, petrol station, monument, superstore, street name signs, railway station, church (Top 10 landmarks, for the complete list please see Burnett, 1998)
May et al. (2001)	Loughborough, UK	Evaluations of a route instruction system (vehicular navigation)	Bridge, church, car park, garage, MacDonalds, Sainsburys[116] supermarket, pedestrian lights, post

[116] Researchers noted that MacDonalds and Sainsburys supermarket were coded as separate items due to the frequency of their use, and the non-use of other similar objects

			office, petrol station, public house
May et al. (2003)	Loughborough, UK	Pedestrians' verbal identification of landmarks on memorised and walked-through routes (pedestrian navigation)	Shops, pubs, supermarket, traffic lights, parks, war memorial, pelican crossings, car parks, shopping center, restaurants, shopping precinct, town hall
Baus et al. (2007)	The University of Saarbrücken, Germany	Audio (non-speech) perceptible landmarks in mobile navigation systems (pedestrian navigation)	Café and restaurant, traffic lights, fountain, river, shopping mall
Grabler et al. (2008)	San Francisco, USA	Automatic map generation for tourists in their exploratory journey (pedestrian navigation)	Attractions, restaurants, shopping places

In addition to the abovementioned literature, we pursued landmark categories being provided in commercial navigation applications such as those used in Nokia Maps™, Garmin nüvi®, and Microsoft AutoRoute®. Landmarks in these commercial systems are generally known as points of interest (POI) and aimed at both vehicular and pedestrian guidance. A summary of these landmarks is provided in Table A2.2.

Table A2.2 Summary of the list of landmarks in commercial applications

Applications	Manufacturer	List of landmarks
Nokia Maps™ 2.0	Nokia (2007)	Airports, amusement parks, at the water (ocean and sea), attractions, bars and pubs, bridges, camping areas, car rentals, ATM, casinos, cinemas, educational institutes, convention centers, ferries, financial services, first aid, golf courses, hospital, hotels, internet/Wi-Fi, libraries, shopping malls, supermarkets, monuments & memorials, museums & galleries, parking, party & clubbing, petrol stations, police, post office, bus/tram/boat stations, railway stations, religious places, restaurants, river, sports facilities, taxis, theatres, toilets, traffic lights, tourist information (over 40+ categories and growing, custom category not allowed)
Garmin nüvi®	Garmin	Bowling, caravan and camping, castles, church, cinemas, DIY-car services, educational institutes, English heritage, football fields, government offices, horse racing, hotels, karting, live music, misc leisure, mountains, museums, National trust sites, racing, paintball, parking, petrol stations, play area, prisons, Red cross, restaurants, sailing, shopping malls, ski and snowboard, sport centers, studios, supermarkets, swimming pools, theme

		parks, Underground/train/bus stations,Wi-fi, youth hostels, zoo (custom category allowed)
Microsoft AutoRoute®	Microsoft (2007)	Airports (major), airports (minor), amusement parks, ATM, attractions, bank, bars and pubs, border crossings, bridges, bus stations, camping areas, car rentals, casinos, champion markets, church, cinemas, city/town halls, civic/community center, convention/business centre, DIY-car services, educational institutes, English heritage, entertainment, ferry terminals, golf courses, grocery stores, hospitals, hotels (with specific chains, e.g. Travellodge, PremierInn), IKEA, monuments, museums, libraries, National trust, parking, party & clubbing, petrol stations, pharmacies, police, post offices, restaurants, shopping malls (with specific chains, e.g. Debenhams), sports facilities, river, supermarkets (with specific chain store, e.g. Tesco, Morrisons), tourist information, train station, traffic lights, UK accident black spots, UNESCO World Heritage Sites, Wi-Fi (over 60+ categories and growing, custom category <u>not</u> allowed)

Researchers (Safelin et al., 2005; Tscheligi & Safelin, 2006) informed that different participants called the same place widely differently (with the exception of bigger chains like Starbucks or Tesco). With regard to such a phenomenon, prior to our main empirical study, we ran several pilot interviewing sessions in an attempt to regroup and classify these landmarks, e.g. to have a higher level of abstraction or to have fine detail landmarks. Feedback from these sessions confirmed the current level of abstraction as appropriate. For example, using higher level abstractions, e.g. grouping *monument*, *museum*, *memorial* and *gallery* into a *tourist attraction* category, would be less useful for navigation since *tourist attraction* is often too generic to make identification easy on the ground. On the other hand, providing finer detail, e.g. identifying each individual landmark as specifically as possible, would make the set of landmarks unmanageably large. This is a particular problem when moving towards our ultimate goal of tactile representation of landmarks, given the challenges of tactilely representing a large set of distinguishable semantics. To mitigate the forced choice nature of the resulting questionnaire, we provided free text areas where participants could report landmarks that were not included in our set.

Our final list that would be used in the questionnaire study included the following landmarks (in alphabetical order):

1. Airports
2. Amusement parks
3. At the water (ocean and sea)
4. Attractions (tourist attractions)

5. Bars and Pubs
6. Bridges
7. Camping areas
8. Car rentals
9. Cash dispensers (ATM)
10. Casinos
11. Cinemas
12. Educational institutes
13. Fairs & Conventions
14. Ferries
15. Financial services (Banks)
16. First aid
17. Golf courses
18. Government facilities
19. Hospital healthcare
20. Hotels
21. Internet/Wi-Fi
22. Libraries
23. Malls and Markets (shopping centre, supermarket)
24. Monuments & Memorials
25. Mountains
26. Music & Culture venues
27. Museums & Galleries
28. Natural barriers (any object that prevents you from moving forward, e.g. roads.)
29. Parking
30. Party & Clubbing
31. Pedestrian lights
32. Petrol stations
33. Police
34. Post office
35. Public transports (bus/tram/boat stations)
36. Railway stations
37. Recreation grounds
38. Religious places (church/cathedral/etc)

39. Restaurants
40. River
41. Sports facilities
42. Stadiums (sports)
43. Taxis
44. Theatres
45. Toilets
46. Travel agencies
47. Traffic lights
48. Tourist information
49. Tunnels
50. Other landmarks

A2.2 Descriptive analysis of landmark's importance and usage

Before each participant answered questionnaires or interviewing questions according to specific navigation purposes, we asked them to rate the importance of having landmark information in the case that they had to travel in familiar and unfamiliar areas. Table A2.3 demonstrates such subjective importance scores of all 160 respondents.

A paired-samples t-test showed significant difference that on average, pedestrians valued that the presence of landmarks was more important to their navigation success when traveling in unfamiliar areas (M = 0.99, SD = 0.08) than in familiar areas (M = 0.48, SD = 0.50), t(159) = -13.09, $p < 0.002$.

Table A2.4 shows overall percentages of landmark use for different navigation purposes from both the 100 online surveys and the 60 face-to-face interviews. There was a large difference in the percentage of reported landmark use for commuting between the online and face-to-face participants (52% *vs* 5%). Qualitative information gathered from the online questionnaires and interviews explained this difference. Commuters (from online) in large, homogeneous cities, especially those with grid layouts, tend to rely on landmarks as navigation cues because different streets look very similar and good landmarks support their orientation and wayfinding decisions. In contrast, our face-to-face interviews were conducted in a relatively old but small city with short routes and diverse interconnected passageways and architectures. In this context, orientation and wayfinding was easy for regular commuters, who have developed a cognitive map of the place and therefore did not rely on prominent landmarks.

Table A2.3 Subjective level of importance of landmarks when navigating in familiar and unfamiliar areas (scores n of 100)

Familiar Areas		Unfamiliar Areas	
Online respondents	Interview respondents	Online respondents	Interview respondents
57	32	100	98

Table A2.4 Overall Percentage (%) of Landmark Use

Navigation Purpose	Familiar Area		Unfamiliar Area	
	Online	Interview	Online	Interview
Commute	52	5	-	-
Quest	-	-	75	95
Explore	-	-	62	90

For online respondents, a one-way repeated-measure ANOVA with navigation purpose as the independent variable was used to analyse the results. It was revealed that navigation purposes had a significant effect on the level of landmark usage, $F(1.96, 193.72) = 6.34$, $p < 0.05$). Post hoc Bonferroni pairwise comparison found a significant difference in the level of landmark usage between commute and quest journeys ($p < 0.05$) but did not find a significant effect between the other pairs.

For face-to-face participants, an ANOVA with navigation purpose as an independent variable was calculated. Results showed that there was a significant effect of navigation purposes on the level of landmark use, $F(2, 57) = 78.82$, $p < 0.05$). Post hoc pairwise comparisons showed that pedestrians significantly relied on landmarks during questing and exploration journeys more than during commuting in each case ($p < 0.002$).

Results from online participants

Of the 52 online participants who reported using landmarks to aid commuting, 48 (92%) used only landmarks in the physical spaces through which they were navigating while the other four stated that they used landmarks both in the physical spaces and on public map displays. Their qualitative responses explained that the areas in which these 4 pedestrians commuted are large transportation hubs, such as a main train station and an airport, and mega department stores where the interior components and structures look alike. They are crowded places and pedestrians needed an orientation aid to maintain their pace. This was achieved by glancing at the public maps provided on display stands along their routes.

Of the 75 online participants who reported using landmarks during a questing journey, 36 (48%) used landmarks only in the physical spaces, whilst the other 39 (52%) matched landmarks in maps and the physical spaces to aid their navigation.

Of the 62 online participants who reported using landmarks during an exploring journey, 15 (24%) reported using landmarks only in physical spaces whilst the other 47 (76%) used landmarks both in the physical spaces and on maps.

As the results are not normally distributed, we ran non-parametric statistics. We ran Friedman's ANOVA for our 100 within participants. For the overall percentage of landmark use, Friedman's ANOVA found a significant difference in the number of landmarks used (both physical and in maps) across the 3 navigational purposes ($\chi2(2) = 12.03$, $p = 0.002$). Wilcoxon tests were used to follow up this finding. A Bonferroni correction was applied and so all effects are reported at a 0.0167 level of significance. There were no significant differences in the number of landmarks (both physical and in maps) used between quest and explore ($T = 315$, $r = -0.17$) and between commute and explore ($T = 891$, $r = -0.18$). However, participants used significantly more landmarks (both physical and in maps) when questing ($T = 943.5$, $r = -0.34$) than when commuting.

Although overall results demonstrated that there was little difference in landmark use for different navigation purposes from online participants (see Appendix 2 Table A2.4), the detailed data show that the number and frequency of landmarks used are very different for different navigation purposes. For example, commuters might use landmarks only once or twice during the whole journey whilst pedestrians who quested or explored referred to a variety of landmarks frequently throughout their journeys. Prior to the study, we predicted that pedestrians would depend most on landmarks during their exploration trip; however, our results indicated that they used landmarks most whilst questing. The qualitative data revealed the reason for this to be that many explorers preferred 'getting lost in space' to truly appreciate the exploratory experience.

Results from face-to-face participants

The face-to-face interviews yielded the following results. There was only one commuter, who stated that he always looks at one particular physical landmark during his (frequent) performance of this commuting journey.

Of the 19 people who used landmarks during questing, 6 (31.5%) used landmarks in the physical spaces, whilst the other 13 (68.5%) matched landmarks on maps and in the physical spaces to aid their navigation.

Of the 18 "explorers", 1 (5.5%) depended on landmarks in physical space whilst the other 17 (94.5%) matched physical landmarks to landmarks on maps.

As our results are not normally distributed, we ran non-parametric statistics. In contrast to our online participants, participants across the 3 navigation purposes from our interview sessions are independent groups. Hence, we used the Kruskal-Wallis Test. A Kruskal-Wallis test showed that the number of landmarks used by the face-to-face interviewees was significantly affected by navigation purpose, $H(2) = 43.33$, $p < 0.002$. Mann-Whitney tests were used to follow up this finding. A Bonferroni correction was applied and so all effects are reported at a 0.0167 level of significance. There were no significant differences in the number of landmarks used between questing and exploring ($U = 190$, $r = -0.09$). However, participants used significantly more landmarks when questing ($U = 20$, $r = -0.88$) and when exploring ($U = 30$, $r = -0.84$) than when commuting.

A2.3 Detailed results

Tables A2.5 and A2.6 show the online questionnaires' results; Table A2.6 presents a list of most common landmarks that pedestrians (subjectively) considered very important in general, rather than important for the particular journeys described in Table A2.5. Table A2.7 presents results of the interview sessions.

Table A2.6 corroborates the finding in Table A2.5 that Mall & Market is very important as a navigation cue because it appears consistently across all three navigation purposes. The category 'Well-known shops/business' emerges in the commuting and the questing purposes because pedestrians referred to landmarks by their brands, e.g. McDonald's was one of the most frequently used landmarks. Similarly, the category 'Other unique landmark' appeared fourth in the explore column because pedestrians did not refer to some symbolic landmarks of the cities as tourist attractions but rather by their unique names, e.g. the Eiffel Tower (see Section 2.1.3 for an explanation).

Table A2.5 Top Ranked Landmarks in Cities Worldwide with Their Frequency (F) and Importance (I) Scores (from Online Questionnaires)

Purpose	Top Landmarks	F Scores	I Scores
Commute	Mall and Market	32	96
	Traffic light	32	91
	Public transport	31	87
	Bridge	31	73
	Financial service	29	74
Quest	Mall and Market	40	113
	Bridge	38	110
	Railway stations	31	91
	Tourist attraction	31	89
	Religious place	32	85
	Traffic light	33	83
	Restaurant	33	81
Explore	Tourist attraction	41	131
	Hotels	30	96
	Mall and Market	32	93
	Bridge	33	83
	Monument and Memorial	28	89
	Religious place	29	81
	Public transport	25	73

Table A2.6 Most Important Landmarks with Their Ranking (R) Scores (from Online Questionnaires)

Purpose	Top Landmarks	R Scores
Commute	Well-known shops / business	111
	Mall and Market	107
	Traffic light	99
	Public transport	82
	ATM	75
	Educational institute	53
	Bridge	48
Quest	Mall and Market	147
	Well-known shops / business	134
	Bridge	103
	Tourist attraction	97
	Hotels	86
	Religious place	75
	Restaurant	67
Explore	Tourist attraction	145
	Hotels	87
	Mall and Market	83
	Other unique landmarks	74
	Monument and Memorial	66
	Railway station	62
	Religious place	52

Table A2.7 shows similar rankings of landmarks in a single city from the face-to-face interviews. Journey specific frequency, journey specific importance and general importance rankings were calculated in the same way as for the online questionnaire results presented in Tables A2.5 and A2.6. (Since the results from the face-to-face interviews were less diverse than the results from the online questionnaires, it is possible to present the face-to-face interview results in a single table.)

Table A2.7 Top Ranked Landmarks in the city of Bath with Their Frequency (F), Importance (I), and Ranking (R) Scores (from Interviews)

Purpose	Top Landmarks	F	I	R
Commute	Monument and Memorial	1	2	7
Quest	Mall and Market	8	25	42
	Public transport	7	23	32
	River	7	22	36
	Religious place	7	20	35
	Bar and Pub	7	15	31
	Railway Station	5	18	30
	Monument and Memorial	5	15	15
Explore	Tourist attraction	18	64	114
	Railway station	16	58	66
	Museum and Gallery	17	52	76
	Monument and Memorial	16	50	44
	River	17	44	22
	Public transport	13	47	60
	Religious place	14	38	27

A2.4 Low-ranked landmarks

We have got our results based on urban space in 43 cities across the globe from both online and face-to-face respondents. There were a considerable number of landmark categories which had rarely or never been used to aid our respondents' navigation. Table A2.8 lists low-ranked and not-chosen landmarks from the online questionnaires and face-to-face interviews. We could see quite clearly from the table that the city where we conducted the face-to-face interviews offers much fewer landmarks compared to other larger cities.

Our collection of landmarks contains 50 categories for participants to choose for their different navigation purposes in different locations. As we mentioned at the beginning, we derived the list from research and commercial applications designed for both vehicular drivers and pedestrians. We left those landmark categories seemed to be designed for vehicles in our list for a number of reasons. We were aware that there was a chance that some of those generic landmark categories may not exist or be close to walking areas in some cities. However, we acknowledge that in different parts of the world, the design of cities and 'pedestrian space' could be varied. Although it is broadly assumed that component parts and design properties of pedestrian environments are widely replicated to contain similar structures and facilities (Zacharias, 2001), it is possible that some areas are large enough to contain broader landmark categories in their walking space. We may look at the difference between walking spaces in cities in Europe and in the U.S.A. Since 1970, a few cities in Europe, for example Stockholm and Copenhagen, have been redesigned to be *full pedestrianisation* (complete removal of noncommercial vehicular access), walking routes usually starting from the railway station (Zacharias, 2001). Zacharias (2001) summarised that the development of the walking environments in European cities encompass whole districts with public institutions and resident use together with the shopping street. There have been attempts to mimic the same success but on a larger scale in numerous areas in the U.S.A., given the country's nature and morphology. As a result, the much larger pedestrian areas in the United States contain more possible landmark categories within spaces (Zacharias, 2001).

The difference in space design in different parts of the world may help explain the phenomenon we observed in Table A2.8. The city of Bath, where the face-to-face interviews took place is a small-size, old city where most of the buildings look the same (as it is registered as a world heritage site; every building has to follow the council regulations on building design.). The city does not have, for example, a big sports stadium, an airport or an amusement park. Many landmark categories served as basic amenity and facilities that travellers may need during their course of navigation but not depend on as crucial navigation cues.

On the other hand, results from online respondents showed that all 50 categories had been used, though some with low frequency. This confirms that different walking spaces elsewhere must contain a number of, if not all, landmark categories provided in our collection. There was a similar pattern as in the face-to-face results on the low usage of public facilities such as toilet or Wi-fi as navigation cues.

For both face-to-face and online respondents, landmarks that lack good characteristics (e.g. recreational ground, travel agency) were not chosen or were rarely being used as navigation cues.

Table A2.8 Side-by-Side comparison of low-ranked landmarks (in descending order of scores)

Purpose	Low-ranked landmarks from Online questionnaires	Not-chosen landmarks From face-to-face interview
Commute	Mountains Airports Fairs & Conventions Amusement Parks Ferries Sports facilities Stadiums (sports) First Aid Recreation grounds Theatres Taxis Toilets Car rentals Internet/Wi-Fi Party and Clubbing Music and Culture venues Travel agencies Golf courses Casinos	All except Monument
Quest	Libraries Mountains Stadiums (sports) Car rentals Fairs & Conventions Theatres Toilets Ferries Recreation grounds Internet/Wi-Fi Amusement Parks Sports facilities Taxis First Aid Casinos Golf courses Travel agencies	Petrol stations Pedestrian lights Music and Culture venues Museums & Galleries Internet/Wi-Fi Taxis Cash dispensers (ATM) Traffic lights Financial Services (Banks) Camping areas Tunnels Travel agencies Tourist information Toilets Theatres Stadiums (sports) Sports facilities Post office Police Party and Clubbing Libraries Hospital healthcare Government facilities Golf courses

		First Aid Ferries Fairs & Conventions Cinemas Casinos Car rentals At the water (ocean and sea) Amusement Parks Airports
Explore	Bars and Pubs Pedestrian lights Government facilities Petrol stations Ferries Post office Fairs & Conventions Cash dispensers (ATM) Hospital healthcare Mountains Parking Police Theatres Car rentals Music and Culture venues Taxis Toilets Amusement Parks Financial Services (Banks) Internet/Wi-Fi Recreation grounds Tunnels Cinemas Sports facilities Stadiums (sports) Libraries Party and Clubbing Casinos Golf courses Travel agencies First Aid	Airports Amusement Parks At the water (ocean and sea) Camping areas Car rentals Cash dispensers (ATM) Casinos Cinemas Fairs & Conventions Ferries Financial Services (Banks) First Aid Golf courses Government facilities Hospital healthcare Internet/Wi-Fi Libraries Mountains Natural barriers (any object that prevents you from moving forward, e.g. fences. Then you might have to deviate to cross that barrier and continue your journey.) Parking Party and Clubbing Petrol stations Police Post office Recreation grounds Sports facilities Stadiums (sports) Taxis Theatres Travel agencies Tunnels

Appendix 3 The Modified Technology Acceptance Model (TAM)

A3.1 The modified TAM

Technology Acceptance Model (TAM) incorporates two multi-item measurement scales: usefulness (U) – the degree to which a user believes that using the system will enhance their performance and ease of use (EOU) – the degree to which the user believes that using the system will be free from effort (See the original scales in Davis, 1989).

We have modified the original scales so that wordings were suitable for the characteristics of the tasks in our experiment. The refined scales of U and EOU are listed below.

1. Perceived usefulness

	Strongly Agree			**Neutral**			**Strongly Disagree**
The system enables me to navigate more quickly	1	2	3	4	5	6	7
The system improves my navigation performance	1	2	3	4	5	6	7
The system makes it easier to navigate	1	2	3	4	5	6	7
Overall, I find that the system is useful for navigation	1	2	3	4	5	6	7

2. Perceived ease of use

	Strongly Agree			**Neutral**			**Strongly Disagree**
Learning to use the system is easy	1	2	3	4	5	6	7
It does not take a lot of effort to become skillful at using the system	1	2	3	4	5	6	7
Interaction with the system is clear & understandable	1	2	3	4	5	6	7
Overall, I find that the system is easy to use	1	2	3	4	5	6	7

A3.2 TAM Development

At the time of this study, TAM (Davis, 1989; 1993) has been continuously expanded to include more factors in order to address the constantly changing IT environments. Extended work include TAM2 (Vankatesh, 2000; Vankatesh & Davis, 2000), The Unified Theory of Acceptance and Use of Technology (UTAUT) (Vankatesh et al., 2003), and TAM3 (Vankatesh & Bala, 2008). These extended versions of TAM are criticised to be overly sophisticated (Bagozzi, 2007). For example, the UTAUT presents the model with 49 independent variables (Vankatesh et al., 2003).

Appendix 4 NASA Task Load Index (NASA-TLX)

A4.1 The modified TLX

NASA-TLX[117] was originally based on the assumption that "workload is a hypothetical construct that represents the cost incurred by a human operator to achieve a particular level of performance" (Geddie et al., 2001). The TLX is a multidimensional rating technique comprising of three groups of workload characteristics: task, behavioral and individual. Characteristics of the task comprises of mental, physical, and temporal demands. Behavioral characteristics include performance and effort. Individual characteristic is frustration. Each of the subscales of NASA-TLX consists of 20 five-point steps from 0-100; the endpoints have verbal descriptors, e.g. Low/High and Good/Poor (Hart & Staveland, 1988).

In our study, we discarded the TLX's weighting procedure as it was reported to be ineffective by Nygren (1991) and Moroney et al. (1992). We used the paper version of the NASA-TLX measures because it was reported to incur less workload than the computer-based version (Noyes & Bruneau, 2007).

We modified the original TLX's questions so that wordings were suitable for measuring workload aspects of a wearable device being used for navigation tasks. The subscales and endpoint descriptors remain the same as the original TLX. The six questions that appeared in our questionnaires are as follows:

Mental demand: How mentally demanding was the task?
Physical demand: How physically demanding was the task?
Temporal demand: How hurried or rushed was the pace of the task?
Performance: How successful were you at accomplishing what you were asked to do?
Effort: How hard did you have to work to accomplish your level of performance?
Frustration: How insecure, discouraged, irritated, stressed, and annoyed were you?

[117] See Hart & Staveland, 1988.

Appendix 5 Additional Information for Chapter 5

A5.1 A list of landmarks

The landmark list contained seven types: Bath abbey, restaurant, public transportation, monument and memorial, mall and market, bridge and tourist attractions.

A5.2 Summary of turning points

Table A5.1 A summary of turning points by direction.

Direction	Number of Turns	
	Route 1	Route 2
Left	3	3
Half left	1	1
Straight	2	2
Half right	1	1
Right	4	4

A5.3 Experimental route 1

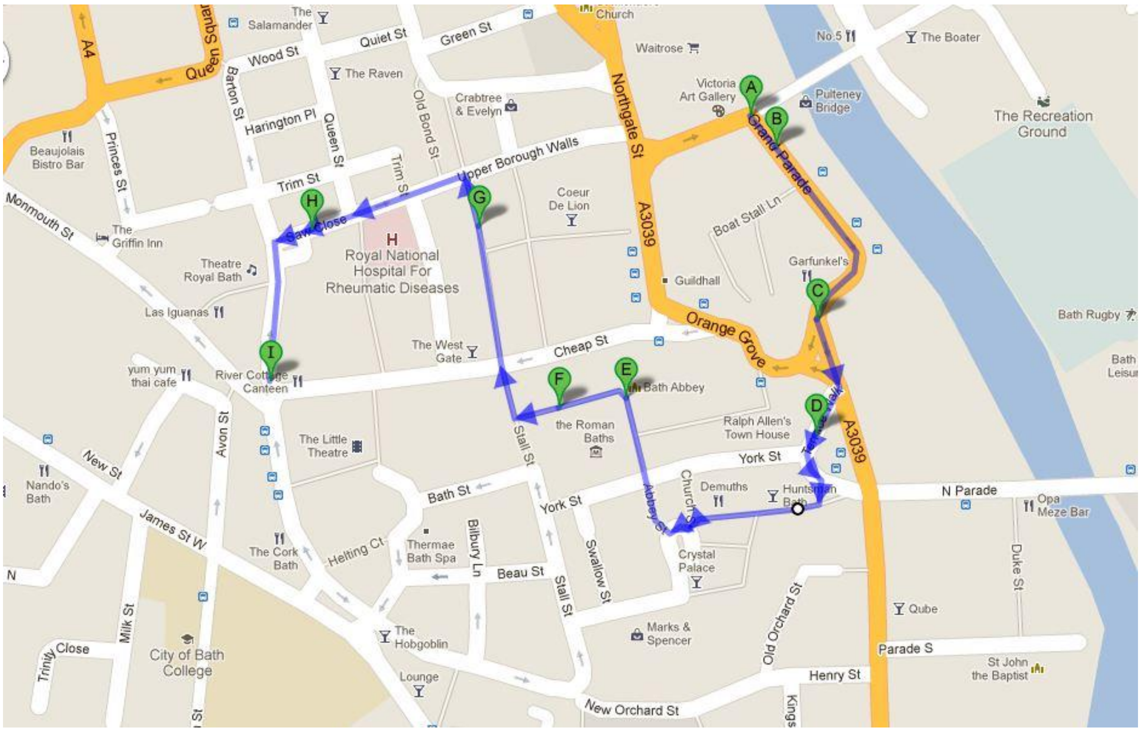


Figure A5.1 Experimental route 1

A5.4 Experimental route 2

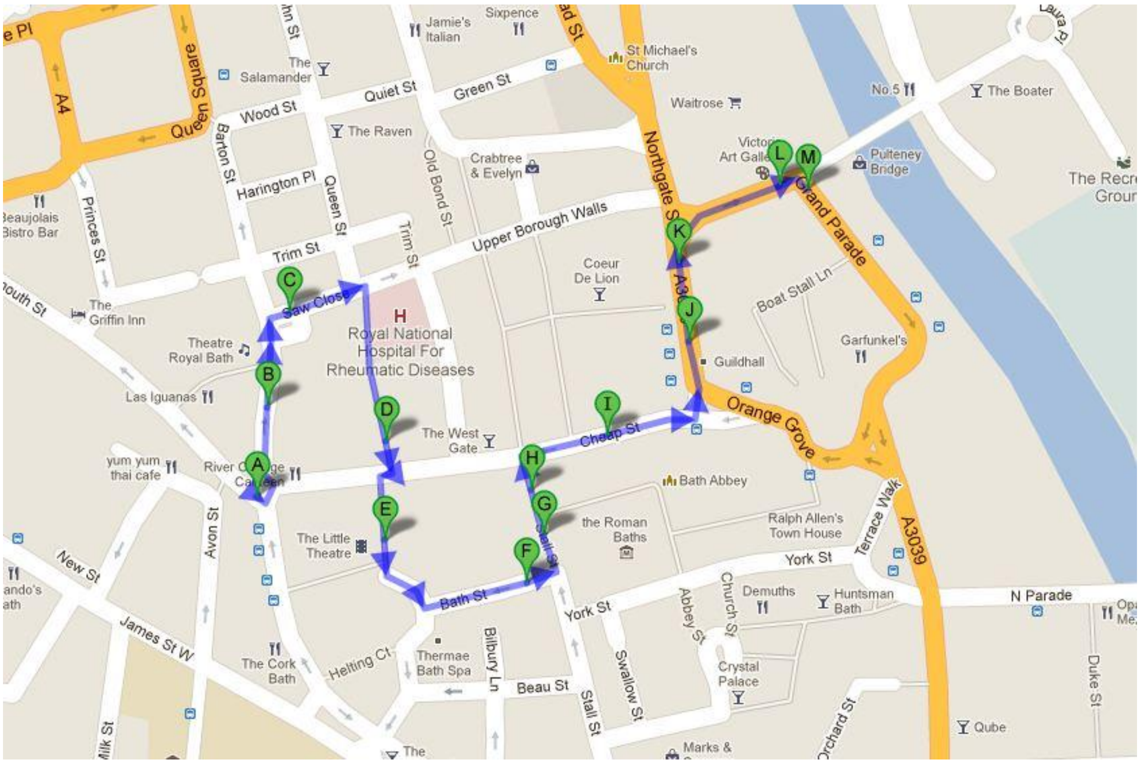


Figure A5.2 Experimental route 2

Appendix 6 NASA TLX for Chapter 5

A6.1 Training T1's NASA TLX scores of two groups of participants

Table A6.1 T1's NASA TLX mean scores of two groups of participants (* indicates significant difference).

Index	Participants	
	With diagram	Without diagram
Mental demand	46.00	63.00
Physical demand	12.00	19.00
Temporal demand	30.50	33.00
Performance*	10.50	21.50
Effort	46.00	56.50
Frustration*	9.50	39.00

A6.2 NASA TLX scores of all sessions: two training and two walking conditions

Table A6.2 NASA TLX mean scores of all experimental sessions (* indicates significant difference between two training conditions, ^ indicates significant difference between two walking conditions).

Index	Training		Walking	
	T1	T2	SS	LM
Mental demand*^	54.50	32.50	33.00	50.25
Physical demand	15.50	12.50	22.00	23.00
Temporal demand*	31.75	22.00	26.50	33.50
Performance ^	16.00	14.25	27.00	39.25
Effort*^	51.25	30.00	30.50	47.75
Frustration^	24.25	16.25	20.50	31.00

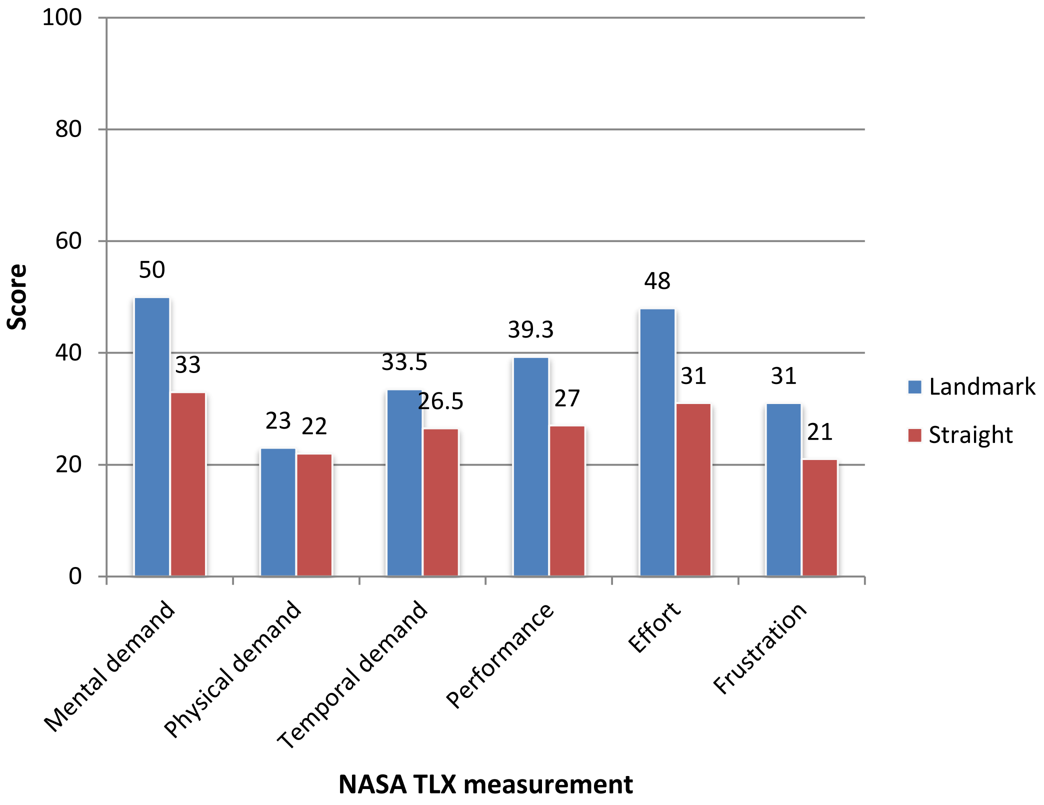


Figure A6.1 Cognitive workload requirements of two walking conditions: SS and LM.

A6.3 NASA TLX scores of male and female participants in two training sessions

Table A6.3 NASA TLX mean scores of male and female participants in two training sessions (* indicates significant difference).

Index	Training 1		Training 2	
	Male	**Female**	**Male**	**Female**
Mental demand	60.00	49.00	42.00	23.00
Physical demand	15.50	15.50	15.00	10.00
Temporal demand	26.50	37.00	21.00	23.00
Performance	12.50	19.50	13.50	15.00
Effort	57.50	45.00	38.50	21.50
Frustration*	34.00	14.50	23.50	9.00

A6.4 NASA TLX scores of male and female participants in two walking conditions

Table A6.4 NASA TLX mean scores of male and female participants in two walking conditions (* indicates significant difference).

Index	Condition SS		Condition LM	
	Male	**Female**	**Male**	**Female**
Mental demand*	39.00	27.00	52.50	48.00
Physical demand*	25.50	18.50	28.50	17.50
Temporal demand	32.50	20.50	40.00	27.00
Performance	22.50	31.50	38.50	40.00
Effort	28.50	32.50	47.50	48.00
Frustration	27.00	17.00	36.00	26.00

Appendix 7 Department of Computer Science 13-Point Ethics Check List

This document describes the 13 issues that need to be considered carefully before students or staff involve other people ("participants") for the collection of information as part of their project or research.

1. *Have you prepared a briefing script for volunteers?*
   You must explain to people what they will be required to do, the kind of data you will be collecting from them and how it will be used.

2. *Will the participants be using any non-standard hardware?*
   Participants should not be exposed to any risks associated with the use of non-standard equipment: anything other than pen and paper or typical interaction with PCs on desks is considered non-standard.

3. *Is there any intentional deception of the participants?*
   Withholding information or misleading participants is unacceptable if participants are likely to object or show unease when debriefed.

4. *How will participants voluntarily give consent?*
   If the results of the evaluation are likely to be used beyond the term of the project (for example, the software is to be deployed, or the data is to be published), then signed consent is necessary. A separate consent form should be signed by each participant.

5. *Will the participants be exposed to any risks greater than those encountered in their normal work life?*
   Investigators have a responsibility to protect participants from physical and mental harm during the investigation. The risk of harm must be no greater than in ordinary life.

6. *Are you offering any incentive to the participants?*
   The payment of participants must not be used to induce them to risk harm beyond that which they risk without payment in their normal lifestyle.

7. *Are any of your participants under the age of 16?*
   Parental consent is required for participants under the age of 16.

8. *Do any of your participants have an impairment that will limit their understanding or communication?*
   Additional consent is required for participants with impairments.

9. *Are you in a position of authority or influence over any of your participants?*
   A position of authority or influence over any participant must not be allowed to pressurise participants to take part in, or remain in, any experiment.

10. *Will the participants be informed that they could withdraw at any time?*
    All participants have the right to withdraw at any time during the investigation. They should be told this in the introductory script.

11. *Will the participants be informed of your contact details?*
    All participants must be able to contact the investigator after the investigation. They should be given the details of the Unit Lecturer or Supervisor as part of the debriefing.

12. *Will participants be de-briefed?*
    The student must provide the participants with sufficient information in the debriefing to enable them to understand the nature of the investigation.

13. *Will the data collected from the participants be stored in an anonymous form?*
    All participant data (hard copy and soft copy) should be stored securely, and in anonymous form.

NAME: ____

SUPERVISOR (*IF APPLICABLE):* ________________________________

SECOND READER (IF APPLICABLE): ____________________________

PROJECT TITLE: ____

DATE: ____

Appendix 8 An Example of a Modified 13-point Ethics Checklist

UNIVERSITY OF BATH,
Department of Computer Science

13-POINT ETHICS CHECK LIST

This document describes the 13 issues that need to be considered carefully before students or staff involve other people ("participants") for the collection of information as part of their project or research.

1. *Have you prepared a briefing script for volunteers?*
   Yes, a briefing script will be prepared (see attachment 1).

2. *Will the participants be using any non-standard hardware?*
   Yes, participants will be using a non-standard hardware (see picture 1 in attachment 2).
   This hardware will generate vibration sensation on the participant's skin.
   There are two types of risks which can occur and they are:
   - Skin Irritation – if the participants feel uncomfortable being stimulated on specific area of their bodies.
   - Experience of over voltage – if any of motors (which generate vibration) is broken. Please note that this condition is not hazardous.

   To prevent these risks, I have performed the followings:
   - Avoid having participants wearing the prototype on sensitive areas such as face. In addition, participants are able to stop the experiment at any time.
   - The prototype has been carefully built and tested by a senior technician, Mr.Vijay Rajput, from Mechanical Engineering Department. In addition to a certified safety warranty from motors' manufacturer (Solarbotics Inc.), Mr. Rajput and I had measured voltage and current produced from each motor in a circuit. Each of the motors has produced a current as low as 28 mA at 3V voltage on average which is under safety threshold[118], called safety extra-low voltage range. If the control voltage switch in the prototype's circuit fails to function, the maximum amount of current is 120 mA at 12V voltage. This means worst case is not hazardous.
     Note: Hazardous condition is when voltage is over 42.4V and current is greater than 120 mA[1].

3. *Is there any intentional deception of the participants?*
   No, there is not.

4. *How will participants voluntarily give consent?*
   There is a consent form which includes the detail of experiments and how their data will be used.

[118] http://fringe.davesource.com/Fringe/Information/Hazardous_Voltage_Primer/

5. *Will the participants be exposed to any risks greater than those encountered in their normal work life?*
There will by physical risks (please refer to explanation in question 2.). This risk is considered lower than those encountered in their normal work life. Example of a comparable condition in participants' normal life is when the participant uses any electronic equipment and plugs it into a wall outlet which has voltage at 240V.

6. *Are you offering any incentive to the participants?*
Yes, there will be a 5 pound monetary incentive.

7. *Are any of your participants under the age of 16?*
No.

8. *Do any of your participants have an impairment that will limit their understanding or communication?*
No.

9. *Are you in a position of authority or influence over any of your participants?*
No, I am not.

10. *Will the participants be informed that they could withdraw at any time?*
Yes. This is written in both a consent form and an instruction form.

11. *Will the participants be informed of your contact details?*
Yes. This information is given in a consent form

12. *Will participants be de-briefed?*
Yes, there is an instruction.

13. *Will the data collected from the participants be stored in an anonymous form?*
Participants will be photographed and video recorded. Each photograph and video recording will be kept with a numerical identifier for each participant. Video data will be kept in a secure location. This data will not be distributed or disclosed to the members of the public.

NAME: Mayuree Srikulwong

SUPERVISOR (*IF APPLICABLE):* Dr Eamonn O'Neill
SECOND READER (IF APPLICABLE): ______________________________

PROJECT TITLE: Synthetic Tactile Feedback at the Human-Computer Interfaces
DATE: December 14th, 2007

Appendix 9 Examples of Ethics Documents

A9.1 An informed consent to participate

INFORMED CONSENT TO PARTICIPATE IN

Evaluation of a tactile pedestrian navigation system

About this study

Miss Mayuree Srikulwong in the Department of Computer Science at the University of Bath is conducting an evaluation of the tactile pedestrian navigation system..

You are being asked to take part in this study by *wearing a waist belt and learn the meaning of vibrotactile signals in order to navigate the city on foot*. All data is recorded for analysis purposes only.

The total time of the experiment is 1 hour 5 minutes. The aims of the study will be explained to you fully during a debriefing after completion of the questionnaire. At this point you can ask any questions you may have. We will provide you with details of the outcome of the study once the research has been completed, if you wish.

Discomfort and risks

This experiment is considered 'minimal risk'; the activities you will be asked to participate in are of no greater risk than those vibrotactile signals (e.g. in mobile phone) encountered in everyday life.

Confidentiality

Your responses will be stored anonymously to protect your privacy.

Your participation

If you agree to voluntarily participate in this evaluation as described, and for any relevant responses to be used in publications anonymously, please indicate your agreement by writing your name, e-mail address, then sign and date below. You will receive 10 pounds incentive in return at the end of study. Thank you for your participation in this research.

Contact information *ms244@cs.bath.ac.uk*

Your Name: ……………………………………………………

Signature: ……………………………………………………

E-Mail: ……………………………………………………

Date: ……………………………………………………

Participant

Number:

A9.2 An overview of the experiment

This experiment:

- Compare **2** different ways of providing confirmation information (that you are on the right path) in a tactile navigation system

You will have to:

Wear a waist belt prototype and learn the meaning of vibrotactile signals in order to navigate the city on foot: by

- Attending 2 training sessions in a lab environment, each session lasts 5-10 minutes.
- Walking **2** different routes
    - For each route, vibration signals for confirmation that you are on the right path will be provided differently, one as a *straight ahead* signal, another as a *landmark* signal.
    - In each route, there are 7 landmarks to be discovered.
    - Each route takes roughly 10 minutes.
- Spending total time of 60 minutes (this includes pause time, time for training and post-study questionnaires)

Your objective

- Navigate the routes in order to reach a destination. You will be told which type of landmarks you will be passing and what the final destination is. At each approaching landmark, you will be asked to say out loud the type of landmark. These landmarks help confirm that you are on the right route.

Your benefit

- Incentive **10 pounds**

A9.3 Instructions of Chapter 5 condition SS

Experiment 5.2

Condition SS Instructions (*Directions* + *Straight ahead signals*)

Summary of condition 1:

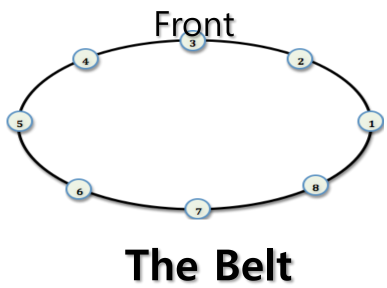
- Getting direction signals from the system as wayfinding instructions
- Getting straight signals as confirmation cues
- Getting destination landmark signals from the system
- Locating a destination landmarks that you plan to visit
- Trying to notice other landmarks along the route that may help you with your navigation

Your objective of this journey is to arrive a destination.

We would like you to imagine yourself being a tourist with a plan to visit **a** landmark in Bath (which you will be told what the landmark is). The system will help you navigate from point A leading to the destination. However, on the route, you will pass other **six** landmarks which may help with your navigation and wayfinding. Please try to locate them. This route is less than 800 metres long. (You will be given the list of these seven landmarks before the experiment begins.)

Before the experiment starts, you will be asked to wear a prototype which generates vibrating sensation (i.e. vibration as felt in mobile phones). You will be asked to carry a backpack, which contains a switchboard.

When the experiment starts, the system will calculate your GPS location and generate vibration feedbacks on your waist corresponding to **directions**, in which you should turn. Vibration is generated 2 times for each turning point, with 3 seconds pause between them. When you are approaching an intended landmark, the system will generate a **destination cue** which is a set of three signals: the cue, the direction of the landmark and the type of the landmark. You will also receive **straight signals** when you pass significant buildings. We would like to encourage you to speak out loud whenever you feel any sensation on your body and tell the experimenter your decision to turn to any direction. If you don't feel any stimuli nor are sure which direction you should turn, please inform the experimenter.



We would like you to try your best to locate and identify all intended landmarks.
If you don't receive any vibration at any junction, please stop for 2-3 seconds because GPS signal might take time to resolve its fixed location. Then please continue to navigate as normal.
If you have a question or problem at any point of the experiment, do ask. You can abort this experiment at any time if you feel uncomfortable. The evaluator will carry a laptop and walk with you as if she were your friend. At the end of this route, you will be asked to fill in a questionnaire and interviewed.

Appendix 10 Codes of practice and procedures

For all studies involving participants, we explained the implications of the experiments clearly, obtained their consent and provided considerable amount of incentives. We made clear with participants that our research did not seek sensitive information that may upset or embarrass them. Nevertheless, all data collected remain confidential and being used only for academic purpose.

For all the signals given by the system, their strength was well within the threshold recommended by fellow researchers. We were aware that the prototype may be misunderstood with a harmful device. As a result, participants were carefully chosen so that they would not possess a stereotypical look of a terrorist and be mistaken by authority. More importantly, we made sure that the risk of walking in the city with the prototype was minimal as we have informed Bath police prior to each walking session.

In order to ensure that we have implemented ethics procedures, we have implemented and followed an experimenter's task list (see an example below).

My Instructions

Make sure that the device and all actuators **work**. Check all types of signals: *direction*, *landmark, orientation* (together with the use of compass), and *destination*

Before start until Training

1. **Greet** a participant and **thank** them for participation
2. **Ask** the participant to take off their outer layer of clothing
3. **Give** them the overview of the experiment
4. **Explain** the experiment in general that they have to wear the device and complete 2 sessions of lab-training and complete 2 routes for 2 walking-conditions. The experiment will take 60 minutes in total.
5. Have the participants **sign** the consent form
6. Have the participant **fill** the pre-study questionnaire
7. **Fit** the device onto their body, make sure that the device fits perfectly
8. **Check** the checklist for randomisation and make sure each participant is run according to plan
    a. **Write** down their corresponding participant number and follow this number throughout every session of the same participant
    b. **Make** sure that they are learning from the system or given the visual demonstration of landmark signals from the random chart

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This thesis symbolises a triumph over tasks both physically and mentally exhausting, achieved by overcoming an unknown yet great fear through perseverance, determination and resilience.

M. Srikulwong, 2012.